THE CLASSIFICATION AND INTERPRETATION OF TIN SMELTING REMAINS FROM SOUTH WEST ENGLAND

A study of the microstructure and chemical composition of tin smelting slags from Devon and Cornwall, and the effect of technological developments upon the character of slags.

Volume I of II

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Artefacts relating to tin smelting from tin mills or 'blowing houses' in Devon and Cornwall, plus material from smelting sites that cover a range of dates from the Bronze Age through to the 19th Century, were examined: these include metallic tin, furnace linings, ore samples and slag.

Analysis of tin slags from over forty sites was carried out, to determine microstructure and chemical composition. Techniques employed included optical and scanning electron microscopy, X-ray fluorescence and ICP mass spectrometry. Analysis indicates that slag appearance and composition are heavily influenced by local geology. Composition, particularly iron content, is shown to have a strong effect on slag melting point and viscosity, and the implications for the purity of metal produced are discussed.

Bringing together the evidence provided by slag chemistry, documentary sources and smelting remains in the archaeological record, changes in tin smelting technology through time, and the consequences thereof, are considered.

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Chapter 1

Introduction

1.1: Introduction

Given the importance of metal production to the economy of the southwest of England, for a period probably in excess of 4,000 years, it is no surprise that this part of the UK is justly famed for its mines and smelters, and although several economically important metal ores, including copper, lead and silver, have been raised in the area, it is popularly renowned for one metal in particular, which occurs nowhere else in mainland Britain: tin. Nor is it surprising to learn how profound a role the extraction of these ores has played in shaping the character of the land in those areas of Devon and Cornwall where they occur. Traces of past tin mining are relatively well represented in the landscape: the granite uplands of Dartmoor bear the scars of extensive earthworks connected with the extraction of the main tin mineral, cassiterite; while in Cornwall the engine houses that served the deep mines are a familiar feature.

What is perhaps surprising is the relative paucity of archaeological artefacts and structural remains relating to one particular aspect of the tin industry: the smelting of the ore into metal. The reasons for this are manifold. Prehistoric smelting is likely to have involved only small superstructures that, even if they were not demolished by the smelters in the course of recovering the metal, would be unlikely to survive millennia of erosion, even without the massive disturbance of the landscape that occurred as a result of larger-scale mining in subsequent centuries (that is assuming that smelting took place close to the area of ore extraction and not in settlements). From at least as early as the Mediaeval period smelting furnaces were housed in custom-constructed buildings known as tin mills or blowing houses, but in Cornwall few of these survive, since in contrast to the situation on Dartmoor many Cornish blowing houses were situated close

to centres of habitation, and they have been dismantled or converted to serve new purposes (see p105), while moulds and other worked stones were carried off for re-use. Even where buildings survive, furnaces were often taken apart at the end of their working lives to recover any tin that had escaped through cracks and pooled beneath them. The multiple-furnace smelting works of the 18th to 20th Centuries fared little better. Again, owing to their general proximity to towns, once the works closed the buildings were demolished and the sites redeveloped. The removal of material from sites was not confined to the buildings and smelting apparatus: waste material could also be taken for reprocessing. Smelting slag always contains residual tin, and from at least the 16th Century it was routinely recycled, usually in the same furnace, but slag was sometimes sold to other smelters (see p421, p426). Slag containing tin that could not be economically recovered in one period could, with improvements in technology, become a valuable resource and old dumps were reworked.

Though much has been lost, particularly in Cornwall, what evidence does remain can be used shed light upon the processes used to obtain tin from its ore. In general, however, the studies of smelting have been piecemeal, concentrating upon one period of history, or on just one of the counties of Devon and Cornwall; moreover, only rarely has scientific analysis been carried out upon any artefact connected with smelting. It is now intended that all the various strands of evidence be brought together, to form an integrated picture of the developments in tin smelting technology used in southwest England from the earliest times and to determine the effects of the changes. To this end, a collection of artefacts – the most extensive to date, covering all periods from the prehistoric through to the early modern, has been assembled, including slag, fragments of furnaces, ores and metallic tin.

The aim of this research is to:

- draw together and assess the available archaeological evidence for tin smelting and to interpret this in relation to documentary descriptions of smelting;
- determine what factors influence the physical appearance and chemical composition of tin slags and relate the observed characteristics to changes in smelting technology;
- show how changing slag chemistry affects the behaviour of slags in the furnace and the quality of the metal obtained;
- create a comprehensive record of slag microstructures and compositional data for reference purposes.

1.2: Previous Work

Finds relating to tin smelting have been reported from several excavations of prehistoric sites (e.g. Hirst 1937; Fox 1957; Guthrie 1969; ApSimon and Greenfield 1972; Miles 1975; Cunliffe 1988; Quinnell 2004), however the discovery of these artefacts was coincidental, and not the *raison d'être* of the excavation. In addition to these, there are finds, particularly of tin metal ingots, from unstratified contexts, which have been attributed to the prehistoric period (see Sections 1.4.1 to 1.4.4).

The excavation of an early Mediaeval longhouse at Crift Farm in Cornwall (SX066603) (McDonnell 1993a, 1993b, 1995) yielded evidence for tin smelting, although the site also appeared to include domestic and agricultural elements in addition to the evidence for metallurgical processes. A newly discovered blowing house at Brownie Cross (SX546609), which possibly dates to the 13th-14th Centuries, was excavated in the summer of 2009 (Taylor 2009, 2010). One later site has been fully excavated: the Post-mediaeval tin mill at Upper Merrivale in Devon (SX55197664) (Gerrard and Greeves 1991, 1992a, 1992b; Greeves 1993b, 1994, 1995; Greeves and Passmore 1996). Apart from a small area in the vicinity of Blowing House Cottage at Godolphin (SW60333205), which was excavated prior to the construction of an extension (Lawson Jones 2000), the work carried out at Crift Farm, Brownie Cross and Upper Merrivale represents the only deliberate modern excavation of a recognized smelting site. Artefacts connected with tin smelting that date from the Mediaeval period and later are therefore generally all surface finds, identified and dated through their association with the structural remains of tin mills.

1.2.1: Tin Slag

Of the material remains of the tin smelting process, potentially the most abundant and informative is smelting slag. That said, however, slag is reported to have been recovered

from only about 60 sites in Britain over the past 100 years. The quantity of material from the vast majority of these sites is very small: most sites have so far yielded only a few kilograms of slag; in some cases only a single fragment has been found.

There is, therefore, a huge discrepancy between the amount of tin metal known to have been produced at various times throughout history, and the amount of slag in the archaeological record. It is quite hard to estimate the levels of production in prehistory, but based on finds of ingots in shipwrecks, it is known that as much as a tonne of tin could be transported in a single shipment (see p34), while individual purchases of up to 4000 kg of tin appear in records from Athens (see p44). It is difficult to estimate the amount of slag that would have been generated during smelting this quantity of metal, as this depends upon the quality of the ore used - it could have varied from almost nothing up to 50% of the mass of metal produced (see p465) – but still the fact that finds of prehistoric slags from Britain amount to only a few grams is striking. By the Mediaeval period production figures indicate that some 300-500 tonnes of tin were being smelted annually (see p80); Mediaeval smelting could, therefore, have generated 100 tonnes or more of slag per year, yet only around a tonne of slag has been found. In the Post-mediaeval period, output rose from 500 tonnes annually to c.1500 tonnes annually; again, however, the total amount of slag that has been located at archaeological sites of this date probably does not exceed 10 tonnes. Slag deriving from furnaces that operated in the 18th to 20th Centuries is even less common: only a few kilograms have been recovered by archaeologists, despite the fact that in the 19th Century, when English tin production was at its peak, over 2000 tonnes of metal were produced annually.

There are several reasons for the shortage of slag: firstly, many slag dumps are deeply buried by later accumulations of matter, including later mining spoil, and only small scatters of stray slag are exposed at surface as a result of weathering and burrowing;

secondly, the ores selected for use were relatively free of gangue (i.e. minerals other than cassiterite) and were also carefully cleaned to remove as much of that gangue as possible, thus the amount of slag produced for a particular quantity of tin metal would be relatively small; finally, recycling of old slag deposits may occur following advances in smelting technology.

Tin smelting slags that date unequivocally to the prehistoric period are extremely rare: samples have been recovered from only two published sites – amounting to 8 pieces in total. The first of these sites is an Early Bronze Age ritual enclosure at Caerloggas, Cornwall (SX01705659), where seven pieces of slag were found (Miles 1972, 1975). The second site is the Late Bronze Age settlement at Dean Moor, Devon (SX678653), where a single tiny bead of slag was discovered in one of the roundhouses (Fox 1957). Slag has also been found in a prehistoric roundhouse at Yes Tor Bottom (SX56697295) (Baring-Gould et al 1898; Worth 1940), and in two of the roundhouses at Metherel (SX66828402 and SX66978412) (Worth 1935, 1937), but at both these sites the slag was recovered from layers containing Late Mediaeval artefacts.

The Mediaeval and Post-mediaeval blowing houses of Dartmoor have accounted for the majority of slag finds. This, to a large extent, results from the work of Greeves, who began investigating the Dartmoor tin industry in the late 1970s, and through visits to smelting sites on the moor over a period of more than 20 years, has amassed a large collection of slag samples. The largest quantity of slag collected to date – an estimated 12,000 pieces – comes from Upper Merrivale (Greeves pers comm. 2002).

Excavations at Crift Farm also yielded a substantial quantity of slag: an estimated 1 tonne (McDonnell 1995), which, taken together with the findings from Upper Merrivale, suggests that other sites may have similarly large dumps.

Slag samples from smelting houses dating to the 19th and 20th Centuries have been obtained by Tylecote (1965, 1966, 1980a, 1989), but the circumstances of their recovery are not recorded in any detail, if at all.

Scarce though tin slag is in the archaeological record, investigations into its physical structure and composition are scarcer still.

In the late 19th Century, the discovery of slag at Yes Tor Bottom (SX56697295) was considered worthy of a half dozen lines in the excavation report, but no analysis of this material was ever carried out, and only six pieces from the assemblage uncovered by the excavation were retained (Baring-Gould et al 1898).

In the 1930s came the first published investigations into the nature of slag, carried out by Worth (1937), who described the physical appearance – colour, surface weathering and morphology – of the slag from Metherel (SX66828402 and SX66978412). Worth made a single thin section for examination of the slag using transmitted and reflected light microscopy, which allowed him to observe tiny beads (or prills) of metallic tin trapped within the slag, but he made no mention of features within the slag itself.

The single bead of slag found at the Dean Moor settlement (SX678653) in the 1950s was examined by Professor Stuart of the Department of Geology at Exeter University, who described it in terms of size, colour, lustre, surface texture and density (Fox 1957). Owing to its very small size, no chemical analysis was carried out, nor ever has been, although Stuart did use chips off the cassiterite pebble found in another hut at the same site to demonstrate that it was possible to create similar beads from this ore; these were not analysed. The Dean Moor slag is unusual in that it is red rather than the usual black or very dark brown.

The first compositional analyses of archaeological tin slags were published by Tylecote in 1965 for early modern slags from dumps at United Mines, Seligan East, Seligan West, Bissoe and Carnelloe (Tylecote 1965, 1966). The sites in question are probably United Mines near St Day (SW750415), Seleggan near Carnkie (SW695402), which had a tin smelting works, as well as the east and west mines of the same name, Bissoe Smelter (SW7741), and Carnelloe Tin Mine near Zennor (SW4438).

Sample selection was not random: Tylecote stated that where possible samples containing metallic prills visible to the naked eye were deliberately chosen over samples that did not contain such inclusions. Analysis was semi-quantitative and was carried out using X-ray fluorescent spectroscopy. The data presented is only partial, giving percentages only of tin, lead, zinc, copper and manganese.

The compositional analysis was in most cases accompanied by an examination of the slag microstructure. The results indicate a highly variable tin content, which may or may not have included metallic prills, and a range of different microstructures.

Tylecote noted that as it is not believed that a smelter was built at United Mines, the slag might have been brought from elsewhere for use as hardcore. He stated that this material was not a copper slag, and proposed that it was a late tin slag, however as it contained only 0.8% tin, this is doubtful (however see the analysis of slag sample 4/05 from Eylesbarrow in Table 3.2). The microstructure of this sample was not examined.

A similarly low tin content (0.5%) was found in the slag from Seligan East, which was believed to be a late, possibly 19th Century tin slag. The slag is reported to have a microstructure consisting of fayalite glass (i.e. iron silicate) containing unidentified thin laths (i.e. needle-like crystals) and evenly distributed round particles of what might be a Sn-Fe phase.

The Seligan West sample is undoubtedly a tin slag. Its 22% tin content is relatively high, particularly for a 19th/20th Century slag, but this figure appears to include the tin content of prills sufficiently large to be visible with the naked eye. These prills contained two phases: probably tin mixed with the tin-iron alloy known as hardhead. The microstructure of this slag consists of unidentified laths and a lighter phase composed of cubic crystals, which Tylecote suggests may be SnO.

The microstructure of the Bissoe slag was not examined. The 60% tin content quoted in the results is extremely high.

The tin content of the Carnelloe sample (2.8% tin) is more typical of a modern slag. Its microstructure is stated to be almost without structure, though some areas had a fine light phase. No metallic prills were observed.

These observations were not linked to the processes and conditions of smelting.

The next slag analysis was carried out a decade later, when the slag from Caerloggas was examined at the Ancient Monuments Laboratory. The report by Biek (Miles 1975) included information on fragment size, colour, morphology, lustre, surface texture, fracture type and density. The slag microstructure was stated to be glassy, following a failure to reveal a crystalline structure by etching, and the slag contained metallic prills, some of which were large enough to be seen with the naked eye. Micro-hardness testing on these prills gave values consistent with their being tin. X-radiography of the sample indicated that these prills were distributed throughout the sample. Compositional analysis of the slag and prills was not published in the initial report, and though subsequently Biek reported that scanning electron microscopy had indicated that the prills were pure tin in an iron silicate slag (Biek 1978), no data were presented.

Full compositional analysis of the Caerloggas slag was not published until 1989, when it was included (allegedly without the permission of Salter who carried out the analysis) in a paper by Tylecote, Photos and Earl (1989). These data are based on a single area scan. Since then, Salter has presented his own more detailed interpretation of this material (Salter 1997), with an analysis of material from Upper Merrivale for comparison (see p14).

What appears to be the first fully quantitative determination of the composition of an archaeological slag was published by Tylecote in 1980, in a paper about the 18th/19th Century smelting site at Calenick (SW820440) (Tylecote 1980a). No details of the method used to obtain this data were supplied, and no microstructural analysis was undertaken. The slag was an unstratified find. Its tin content (7.9% Sn) was described only as 'not abnormal', and Tylecote commented on a possible link between the iron oxide content of the slag and the use of iron oxide fluxes in smelting, but otherwise no attempt was made to relate composition with the smelting process.

A year later Greeves included data obtained from slag samples from eight Mediaeval and Post-mediaeval sites in his doctoral thesis on the Dartmoor tin industry (Greeves 1981a p261). The sites were Eylesbarrow (SX59196765), Gobbett (SX64537280), Outer Down (SX68218658), Riddon (SX67417668), South Hill (SX68018710), Stannon Brook (SX64857955) and Thornworthy (SX67238443). Both X-ray fluorescence analysis and electron microprobe analysis of these samples was carried out by Rod Clough of the Institute of Archaeology, London (Greeves pers comm. 2008). (These results were published in 1989 when they were, like the Caerloggas slag, included in the paper by Tylecote, Photos and Earl (1989).) The electron microprobe analysis showed that the slags were heterogeneous and exhibited a range of microstructures from glassy to crystalline, although it was not stated which samples fell into which category (Greeves 1981a p259). The possibility was raised that higher levels of titanium,

phosphorus and/or zirconium could reflect the type of ore being used, but no other inferences were made regarding methods of production.

Following Greeves' work on the history of the tin industry in Devon, Gerrard undertook similar research focussed upon Cornwall. A detailed examination of the collection of tin processing and smelting buildings at Retallack (SW732300) was carried out by Gerrard (1985), but none of the slag from this site was analysed at this time, and it was only in 1989 that an analysis was published (Tylecote et al 1989). Gerrard also examined the earthwork remains of a smelting site at Hurdon (SX210823) (Gerrard 1986 p279, p281-2), but again no analysis of the slag was carried out. (The first compositional data from this site was obtained by the present author (Malham 1996).)

Further compositional data was published in 1986, when Earl included the analytical results from three pieces of slag from the Post-mediaeval blowing house at Hexworthy (also known as Week Ford) in Devon (SX66187232) in a paper describing his experimental smelting work (Earl 1986). Samples were examined with a scanning electron microscope. The presence of metallic prills in the slag was noted, but these were not analysed. The archaeological slag received only a brief mention, in the context of a comparison with the experimentally produced slags, from which it differed in several particulars.

The Week Ford data was also included in the aforementioned paper by Tylecote, Photos and Earl in 1989, along with Salter's preliminary analysis of the Caerloggas slag, the compositions of Devon slags given by Greeves (1981a p231), and Tylecote's own analysis of the 18th/19th Century Calenick slag. To these were added new data, obtained by Tylecote and his co-authors, using electron microprobe analysis, which allowed the composition of different phases within the slags to be determined. Six of these additional samples were 'Mediaeval' slags: Gobbett (SX64537280), Whitten Knowles

(assumed to be 13-15th Century), Longstone (SX56076880), Caseley (a site also known as Lustleigh) (SX78778216), Crift Farm (SW067602) and Retallack (SW732300). There were also additional samples from four 18th/19th Century smelting furnaces: Angarrack (SW583382), Trereife/Stable Hobba (SW455294), Treloweth (SW537354) and Truro British Legion (SW825450). The paper also included an analysis of one modern i.e. 20th Century smelting slag, taken from Bray (1947 p445), and one early Portuguese slag, believed by Tylecote to be a tin slag, details of which were originally presented in Costa and dos Santos (1965). X-ray mapping of one of the samples from Retallack was used to illustrate how antimony and tungsten were distributed between the slag and the metallic prills trapped in the slag.

This paper was the first to discuss the differences in composition between slags from different periods, and to attempt to link slag composition to smelting conditions. It was noted that early slags have a wastefully high residual tin content, but otherwise there seemed to be little variation in the physical appearance and chemical composition of slags from the Bronze Age to the end of the 17th Century when the blowing houses, which utilized shaft blast furnaces, were phased out and replaced by coal fuelled reverberatory furnaces. The reverberatory slags were reported to have slightly lower tin and silica contents. The microstructures of all the slags were described as glassy (though bands of different composition were noted in some pre-reverberatory slags), with the exception of the Truro slag, which exhibited low and high tin crystalline phases. The presence of prills in certain samples was remarked upon, but although microprobe analysis was apparently carried out on some specimens, no results are presented.

Analytical work on slags from Crift Farm (SW067602) was carried out by the present author and the results were presented in an MPhil thesis in 1996 (Malham 1996), along with analyses of samples from ten other smelting sites. Eight were blowing houses:

Blackaller (SX73808370), Hurdon (SX210823), Longstone (SX56076880), Lower Merrivale (SX55277535), Outer Down (SX68218658), St Agnes/Trevellas Porth (SW7261351923), Stannon Brook (SX64857955) and Week Ford (SX66187232). Two were reverberatory smelters: Charlestown (SX037517) and Trereife (SW455294).

Differences in surface texture and morphology between blowing house and reverberatory slags were noted, with the latter being more massive. Optical microscopy was used to show that the Crift Farm slag and all the blowing house slag samples were glassy and that both reverberatory samples were crystalline. Compositions were determined using energy dispersive scanning electron microscopy: seven samples from Crift Farm and a single sample from each of the other sites were examined. The composition was determined at six points across the surface of each sample, covering an area measuring approximately 160x100μm. The results were seen generally to conform to the previously observed trend that earlier slags had higher tin contents. These data were published in 2002 (Malham et al 2002). Individual crystalline phases within the slags were not analysed. Tin prills were observed in many of the pre-reverberatory slags. Compositional analysis of two particularly large prills was obtained using EDX-SEM, which showed that the prill in one sample was almost pure tin, while the other contained c.1% iron.

Experimental re-melting of samples of slag from Crift Farm demonstrated that the slag began to soften at 850°C, but remained too viscous to pour, even slowly, until the temperature reached 1000°C. These results were used to tentatively conclude that the Crift Farm slag was the by-product of a relatively low temperature smelting process, albeit with a lower temperature limit being set by the viscous behaviour of the slag.

Further work on the Crift Farm slags was undertaken by Aylett, whose undergraduate dissertation contained additional EDX-SEM analysis (Aylett 1996).

Analysis of slag from Crift Farm was also carried out by Adriaens, the results of which were published in 1996 in a paper comparing this slag to material from the Early Bronze Age site at Kestel/Göltepe in Turkey (Adriaens 1996). The analysis appears to have been performed on a single sample from each site. Striations were noted in the Crift Farm slag and the compositions of each phase, as well as the bulk composition of the slag matrix, were determined using wavelength dispersive spectrometry with a scanning electron microprobe. The slag was observed to contain two types of mineral grain, which were shown to be tin oxide and aluminium-silicon oxide. Metallic prills were also observed, and a single analysis obtained, indicating tin containing impurities amounting to <1%. The paper used the similarity between the Crift Farm slag and the Turkish material to conclude that the latter was also a tin slag.

The following year, 1997, saw the publication of the aforementioned paper by Salter, who used optical and scanning electron microscopy to study the microstructure of a single sample from Caerloggas and three from Upper Merrivale. The Caerloggas slag was shown to be glassy with striations that Salter called ‘flow banding’. Occasional clusters of fine needle-like crystals were also noted. In addition, the slag was found to contain inclusions of tin metal, and crystals of cassiterite and zircon. The Upper Merrivale slag also exhibited flow banding, and contained metallic tin prills (albeit smaller and less common than those in the Caerloggas slag) and zircon crystals. The composition of the slag and the phases within it were determined by wavelength dispersive X-ray fluorescence analysis using a scanning electron microscope. Unlike the data published in 1989, the compositions presented were, for Caerloggas, the mean of 20 scans of areas of the sample measuring 30x40μm (the paper erroneously states 30x40mm), and for Upper Merrivale, the mean of 27 area scans. Tin content in the Caerloggas slag was high at 41%; the Upper Merrivale slag contained 18%. Both iron and titanium were found to be lower in the Caerloggas slag. A small amount of the

Caerloggas slag was re-melted, which showed that the material began to soften at 1050°C, but was not fully molten.

In 1998, in his unpublished MPhil thesis for the University of Exeter, Brooke reported 'a crescent shaped heap of rubble and brickwork, with many bricks bearing deposits of slag' at the probable site of Impham Smelter, which was in operation in 1758. Analysis carried out by L.G. Sears of the Camborne School of Mines indicated the slag contained 1.5% tin, iron, silica and aluminium oxide. No details of the methods used to carry out this analysis were provided (Brooke 1998 p230).

Recently, Fielding, a doctoral research student at Johns Hopkins University, Baltimore, USA, has also embarked on a programme of analysis of tin slags from the southwest of England. The results of this work have not yet been published.

To summarize: taking all of the above into account, slag from less than 30 different sites, from all periods from the Bronze Age to the 20th Century, have been subjected to analysis, and in most cases the data was obtained from a single piece of slag. Considering the results of previous work as a whole, it appears that these very small sample sizes have led to an overly simplistic view of slag microstructure and composition. Nonetheless, a range of different features and subtle differences between slags from different periods and locations have begun to be been revealed, which potentially can shed light on smelting practice. To date little attempt has been made to determine the relationship between slag composition and the technology that produced it, thus it is a subject that clearly warrants further investigation.

1.2.2: Tin Ores

Cassiterite (or 'stream tin' as pebbles of this mineral are sometimes known) from archaeological contexts is rarely reported. There are three main reasons why this might

be so: because it is not a waste material, so unlike slag it is not often dumped at smelting sites; because smelting sites are so infrequently excavated; and because cassiterite is a difficult mineral to recognize. That said, a few examples have been recovered, the majority of which are from excavations of prehistoric settlement sites. As additional evidence for smelting within a settlement is usually lacking, it has often been concluded that cassiterite finds indicate that tinworking was part of the economy in a particular area, but that the actual smelting process was carried out outside the settlement (see p38).

A passing mention of finds of stream tin, together with an item that may have been a tin spindle whorl, is included in Noall's account of the dismantling of several presumed Bronze Age barrows in the vicinity of Bussow (SW5039) in about 1910. This was not published until 1971 (Noall 1971), and no further information regarding the stream tin is provided (Penhallurick 1986 p214).

The earliest published archaeological report to mention cassiterite was Hencken's 1933 account of the excavations at the Iron Age settlement at Chysauster (SW472350). One large pebble of what was described as 'rich local tin ore' was found in one of the houses, but it was smoothed on one side as if used as a hammer stone, and as such pebbles are abundant in the local area, it was not thought to provide firm evidence of on-site smelting. The sample was not subjected to analysis at the time. See Section 3.2 for a new examination of this sample.

In the 1935 report on the finds from the prehistoric round houses at Metherel (SX6684), Worth states that a number of pieces of stream tin were recovered from a layer somewhat above the prehistoric floor of Hut 3, which were associated with tin slag (see p7) (Worth 1935). The report carries a photograph of these samples, but no detailed

description. Chemical analysis was not carried out at the time. See Section 3.2 for a new analysis of this material.

Excavations at the 1st Century AD hillfort at Carloggas, St Mawgan in Pyder (SW87356562) yielded a single specimen of cassiterite, which was associated with evidence suggesting a metalworking workshop (Threipland 1956). Analysis, by methods unspecified, gave the following composition: 78.71% Sn (= 100.0% SnO_2), 1.45% SiO_2, 1.4% FeO + Al_2O_3, with Cu, TiO_2 and CaO present at <1%. To date this is the only published analysis of cassiterite from an archaeological context.

The 'tin slag' reported from this site, which Tylecote (1962 p65) interpreted as partially reduced ore, is possibly highly re-oxidized tin metal (see p22).

The report of the excavations at the Bronze Age settlement at Dean Moor (Fox 1957), noted that a single pebble of cassiterite, recovered from the floor of 'Hut 5B', was examined by Prof A Stuart, Department of Geology, Exeter University, who identified the minerals contained within the sample. No chemical analysis was carried out.

Excavations at the Iron Age/Roman period enclosure at Castle Gotha (SX030496) revealed evidence for on-site copper alloy working, amongst which was a single cassiterite pebble (Saunders 1960-1). This find is discussed in more detail in a later report on the site (Saunders and Harris 1982). Its composition was not determined.

Three pieces of cassiterite were discovered during the excavations of the Roman period walled settlement at Goldherring (SW411282), which was excavated in 1958-61 (Guthrie 1969). However, it appears that this site may also have hosted a later, possibly Mediaeval, blowing house. One sample was from relatively high in the strata of the courtyard not far removed from the building interpreted as the blowing house; the other

two came from a pit, rather further away, in an area where minute scraps of bronze were also found. No further details of these samples were provided.

During excavations in 1955 and 1956 at the settlement at Trevisker, St Eval (SW888687), which appears to have first been occupied around 1700 to 1300 BC, a hoard of over 20 cassiterite pebbles was found in Structure B, which on the basis of other finds was identified as a possible bronze-founders workshop. One more pebble was found in House C and two from House A (ApSimon and Greenfield 1972). One representative specimen was examined at the Department of Geology, Queens University, Belfast, where it was confirmed as cassiterite. Subsequently two pebbles were examined at the Cambourne School of Mines, and it was concluded that one of these exhibited characteristics of a distinctive local geological deposit. No chemical analysis has been carried out (Penhallurick 1986 p205).

Two cassiterite pebbles were found in the Early Bronze Age ritual enclosure at Caerloggas (SX01705659) (Miles 1972, 1975). Further information regarding the nature of these pebbles is provided in a paper by Biek (1978): X-ray diffraction was used to confirm the presence of cassiterite (SnO_2), and scanning electron microscopy additionally revealed some iron to be present. The planned report of the analysis of these samples was never published.

Six cassiterite pebbles are listed amongst the finds at Mount Batten (SX487533), a multi-period site (Prehistoric to Mediaeval) excavated in 1979 (Gaskell-Brown and Hugo 1983). It was not clear whether this material related to on-site metalworking or transportation of ore, or to what period. The pebbles were not subjected to analysis.

Samples of cassiterite came from the Roman period settlement at Trethurgy (SX03475564): one each from structures X5, V and Q5 (Quinnell 2004). Further details are not provided.

Three dumps of what appeared to be quartz-tourmaline vein material were excavated in the vicinity of the Upper Merrivale tin mill (SX55197664) (Gerrard and Greeves 1992a). Samples were examined visually and slight traces of cassiterite were noted in some pieces, however the material was interpreted as low-grade ore that had been discarded. For a new analysis of this material see Section 3.2.

With so few of the rare cassiterite finds having been analysed, it is clear that there is scope for further investigation into the chemical make-up of ore samples from archaeological sites; in particular to test the assertion that early smelters utilized ores of extremely high purity.

1.2.3: Furnace Linings

Examples of furnace linings are extremely rare in the archaeological record. No analysis has previously been undertaken.

1.2.4: Tin Metal

Finds of metallic tin have attracted more interest than other material remains of the tin smelting process, no doubt because the production of tin is the reason for carrying out smelting and the metal produced is a valuable commodity. Analysis has focussed on tin ingots, as this is the form in which most archaeological finds of metallic tin occurs. Although occasional finds of small fragments of metal mixed with charcoal have been reported, which may be presumed to be trickles of metal that have escaped from the furnace during smelting, none of these appear to have been analysed.

The earliest published descriptions of discoveries of metallic tin date from the latter half of the 18th Century, and reports containing information about the sizes and forms of ingots, or stray fragments, appear at intervals throughout the 19th and 20th Centuries, with some publications offering additional discussion of surface markings or the

significance of the morphologies of the blocks (Borlase 1758 p163 & Plate 20, 1764; Gregor 1818; Carne 1821; Hitchens and Drew 1824 Vol 2 p587; Hawkins 1832; Bray 1836 Vol 3 p254; Penaluna 1838 Vol 2 p258; Webber 1843; Le Grice 1846; Henwood 1855 Part 2; Way 1859, 1866; Rogers 1861, 1863; James 1863, 1871; Anon 1872; Henwood 1873/4; Evans 1881 p230 p426 p514; Borlase 1882; Hext 1891 p155-6; Haverfield 1894, 1900, 1903, 1924; Rowe 1896 p175; Rogers 1903; Opie 1932; Warner 1967; Piggott 1978; Beagrie 1983, 1985; Penhallurick 1986 p118, p225-236; Fox 1995, 1996). A list of ingots and tin metal finds is given in the Catalogue of Tin Metal Finds (see CD-ROM).

Two 19th century papers include analyses of archaeological specimens of metallic tin. The earliest is by Gregor (1818), who identifies the coating on a find from the parish of Kea (c.SW8143) as muriate of tin (i.e. tin chloride).

A later paper by Collins (1871) concerns the analysis of a tin ingot from Trematthack Moor (c.SW4531). A brittle brown coating on the surface of the block was shown to be largely composed of SnO_2 (90.62%) with traces of metallic tin (0.43%), $SnCl_2$ (1.66%), Fe_2O_3 (1.04%) and SiO_2 (0.41%). Details of the chemical methods for the identification of each component are provided.

Further information relating to the chemical analysis of archaeological ingots was given in 1915 in a paper by Henderson, who reported on the finding of several ingots at Vellin Antron (SW7633). Henderson states that two samples were selected for analysis and two methods were employed, the determinations being carried out at the Williams, Harvey and Co Ltd tin smelter, Hayle. No details relating to the precise chemical techniques used were given. The samples had a composition of 96.88% tin, with traces of iron. The outer surfaces of the ingots were coated with tin oxide.

Examination of a block of 'ore', now believed to be smelted tin metal that has re-oxidized, found within a dubious furnace structure at Chûn Castle (SW40503395) showed it to consist of laminated layers of tin with interstitial patches of an antimony compound (Leeds 1927).

A paper comparing the chemical compositions of several tin ingots was published in 1937 by Smythe, who used unspecified chemical methods to analyse metal from ingots found at Plymouth (now referred to as the St Mawes ingot, or sometimes the Falmouth ingot) (SW8132), Carnanton (SW886640), Penzance (i.e. Trereife) (SW455294) and St Austell (SX0147 to SX0151). The blocks were found to be tin of high purity (99.9% Sn), and free of copper and lead. The microstructures of the Plymouth and Carnanton ingots were examined optically, which showed the metal to have a granular structure with large grain size (although parts of the Plymouth block were composed of smaller grains).

An analysis of the corrosion products on the Plymouth and Trereife ingots was published by Smythe in 1940. The Plymouth ingot was mainly SnO_2 with small amounts of SnO, $SnCl_2$ and SiO_2 (0.41%). Only SnO is identified in the Trereife ingot.

Descriptions of three of these four ingots (St Austell is excluded) were summarized by Tylecote in 1962 (p66-7). Descriptions of all four, plus ingots from five other sites, were included in later publications in 1966 and 1978. Compositions quoted in these works are those previously given by Henderson (1915) and Smythe (1937). Tylecote carried out quantitative analysis, by methods unspecified, of the crusts of ingots from Par Beach (SV932153) identifying them as oxidized tin contaminated with some iron and silica from the burial environment, which he states is also the case for the crusts on the Trematthack Moor and Chûn Castle blocks (1966). It is not clear whether Tylecote himself carried out the examination of the Chûn Castle crust. Information relating to

these same nine ingots was published again by Tylecote in 1986 (p47-9), when details of the size and form of ingots from another six sites were added, along with a summary of corrosion products on tin ingots, which included results obtained by Collins (1871) and Smythe (1940).

The results of the analysis of material from the excavations at Carloggas, St Mawgan in Pyder (SW87356562) published by Threipland (1956) included a fragment of material reported as 'slag', but this was found to contain 79.71% tin metal, with only traces of other elements, which suggests that it was actually either partially reduced ore or, more likely, corroded tin metal. Tylecote (1978, 1986 p51-2) examined a specimen of a crusted plano-convex ingot from this site and gives an analysis of the corrosion product, which was determined by X-ray diffraction to contain 75% SnO and 25% SnO_2. In 1983, when Beagrie was obtaining samples for a new study of tin ingots, he was unable to trace such a specimen, but a few small pieces of tin corrosion product labelled 'Lead?/Tin? Slag ST M 49 House W' (Box 189 St Mawgan in Pydar Excavations) were discovered at Truro Museum (Beagrie 1985). A new analysis of this material is given in Section 3.4.

Analysis was carried out by Biek (1978, 1994) on one of the four ingots discovered at Prah (or Praa) Sands (SW580279) in 1974. The metallic central portion of this ingot was shown, using SEM analysis, to be 99.5% tin, the remainder being iron in the form of crystalline inclusions of intermetallic tin-iron compounds. The thin surface crust was analysed by X-ray diffraction and was found to contain SnO and SnO_2.

A fragment of the ingot found during the excavations at Trethurgy round (SX03475564) in the 1970s (Miles 1973) was analyzed by Bayley using X-ray fluorescence, which showed tin, iron and manganese to be present, the latter believed to derive from the burial environment (Quinnell 2004 p73). Biek (1978) reports that X-ray diffraction of

the crust of this ingot, which accounted for the bulk of the artefact, revealed SnO_2, but no SnO.

On the basis of work carried out to date, compositional analysis appears to indicate that the metal in finished ingots is usually of very good quality. Although this claim is based on results from only six sites, five of those six have been shown to have a tin content of 99.5% or higher, the balance being iron. Such determinations are only possible where un-corroded metal remains: high levels of corrosion make it difficult to determine the purity of the tin in ingots and blocks: the tin oxides and occasionally chlorides that comprise the decomposition crusts may be contaminated by elements, particularly iron and silica, from the burial environment.

As these data were obtained from finished ingots, it is not possible to determine whether any secondary refining of the metal was necessary. It might be suggested, based upon the presence of antimony in the metal from Chûn Castle, that the smelted tin was not always as pure as is usually believed, but it is difficult to draw any conclusions since the identity of this material is so uncertain: it may be a finished ingot, or tin that has escaped from the furnace, or metal brought from a smelting site elsewhere that is awaiting further processing. Analysis of metal from sources other than ingots may help to answer this question.

1.3: The Geological Setting

1.3.1: Tin Minerals

From an economic point of view the sole ore of tin is cassiterite (SnO_2), a chemically stable mineral with a specific gravity of between 6.8 and 7.1. Pure tin oxide is colourless (or white in powdered form), but cassiterite in its natural state is almost always brown or black owing to the presence of impurities in the form of oxides of iron or manganese. The much less common tin mineral stannite (Cu_2FeSnS_4) is also known to occur in the UK.

A black monoxide of tin, called romarchite (SnO), which also occurs in a white hydrated form as hydro-romarchite ($Sn_3O_2(OH)_2$), exists and was first described in 1971, but is known only as a re-oxidation product on tin metal (Roberts, Rapp & Weber 1974 p524).

1.3.2: Tin Deposits: Veins, Shoad and Stream Tin

Tin mineralization is not common on a global scale, and in Europe is confined to discrete regions associated with the granites of the Varsican orogeny. Major deposits are found in southwest England, in the counties of Devon and Cornwall; in the Erzgebirge area of the Bohemian Massif located in southeast Germany and the northwest of the Czech Republic; about the Iberian Massif of northern Portugal and northwestern Spain, with additional scattered deposits in central Spain; and in southern and western parts of the Brittany peninsula, with lesser deposits distributed along the northern edge of the Central Massif of France (Figure 1.1) (Penhallurick 1986 p63-78, p85-104; Merideth 1999 p29-33). Minor deposits occur in the Tuscany region of Italy, on the island of Sardinia (Penhallurick 1986 p79-83), and in the northwest of Serbia

(McGeehan-Liritzis and Taylor 1987; Durman 1997). Further to the east, in Turkey, traces of tin also occur in the Taurus Mountains of Anatolia (Muhly 1973 p257; Penhallurick 1986 p16; Yener and Özbal 1987; Yener, Özbal, Kaptan et al 1989; Yener, Özbal, Minzoni-Deroche and Aksoy 1989).

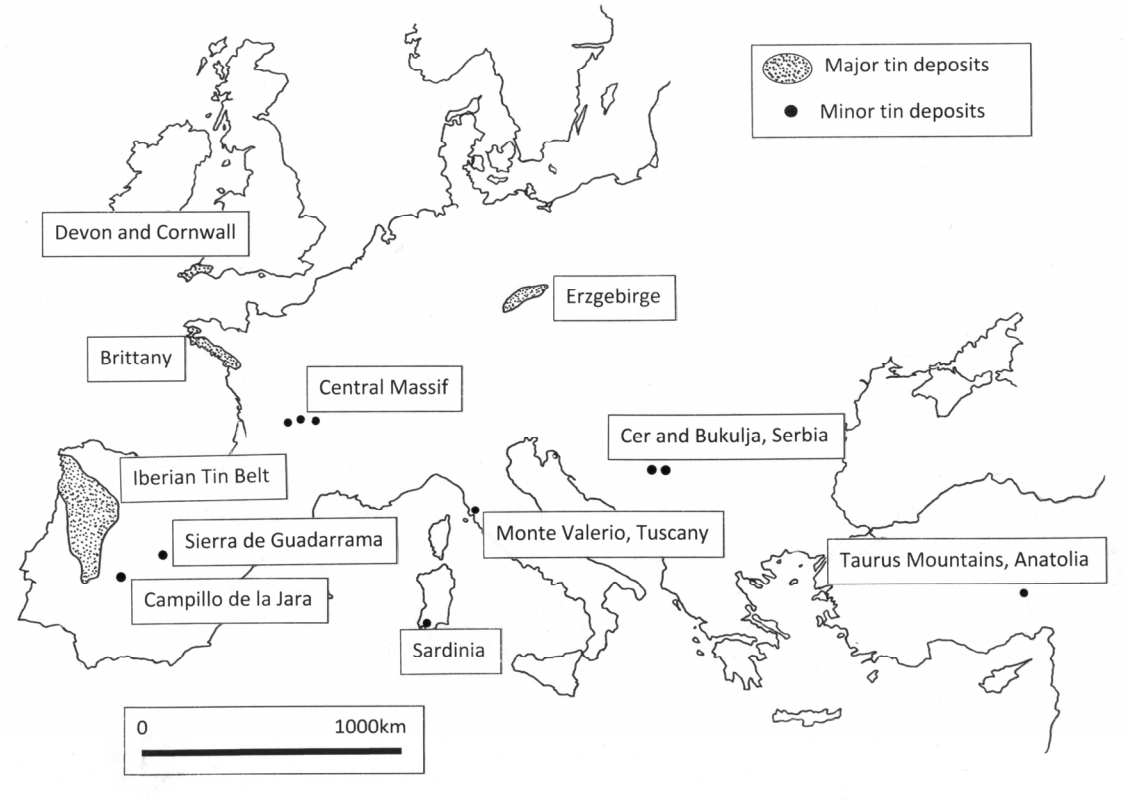


Figure 1.1: Map of European Tin Deposits

In Britain tin occurs in workable quantities only in the southwestern peninsula of England, where it is associated with a series of granite plutons that intruded into pre-existing sedimentary rocks – slaty shales and mudrocks (locally known as killas). Following erosion of the surrounding killas, outcrops of resistant granite now dominate the landscape of Devon and Cornwall. They are generally regions of moorland or rough pasture, with Dartmoor, Bodmin Moor and St Austell Moor being prime examples.

These exposed plutons are merely the upper portions of a single elongate batholith that underlies the whole of the southwest, extending from Dartmoor through to the submerged continental shelf beyond the Isles of Scilly. Despite the common origin of the granite, there is, nonetheless, some variation in the composition of the igneous rocks exposed at surface, most probably as a result of fractionation of chemical species within the melt followed by differential erosion of the batholith. The majority of the granite is coarse type B biotite granite, which may be enriched in lithium, fluorite, topaz or tourmaline. There are also smaller regions where type C biotite granites occur, and more rarely types D to G. Accessory mineralization in all granite types is varied (Alderton 1993 p280-2). Alderton reports that tin (generally present in the range of 5 to 25 ppm) and tungsten seem to be associated with muscovite mica but not biotite mica in type B biotite granites. The distribution of tin within the other types is not known.

Surrounding each pluton is a relatively narrow band in which the country rock has been altered by contact metamorphism. Tin is found in workable amounts mainly within the granite, but also occurs within these metamorphic aureoles and the killas beyond.

The main economic deposits of tin occur as veins created when hydrothermal fluids were released and migrated through the solidifying plutons. These veins or lodes are generally polymetallic, and also contain varied gangue minerals, particularly quartz, tourmaline, chlorite and fluorite.

The thermal gradient around the plutons caused different minerals to be deposited at different distances from the granite. In some cases the resultant zoning takes the form of concentric rings around the granite, but elsewhere the relationship is not so strong. Dines (1956 p60) thus postulated the theory of ‘emanative centres’ to account for the

fact that the behaviour of the fluids was influenced not only by temperature but by the presence or absence of fractures in the surrounding rocks.

Although the above is a highly simplified view, it is clear that tin from veins or lodes may potentially be associated with a large variety of gangue minerals and other ore minerals (e.g. arsenopyrite, wolframite, molybdenite and haematite), the exact nature of which will be dependent upon the local geology.

Weathering of the mineral bodies as they became exposed led to the eventual formation of oxide gossans, with a wide variety of secondary mineralization being developed. A gossan is an iron-capped mineral zone: insoluble iron minerals remain close to the vein surface, while other metallic species such as copper, present as soluble sulphide minerals, are leached out and thus accumulate at depth. The effects of weathering in some gossans have been seen to extend to great depth: 300m and more. In southwest England the upper portions of the gossans would also be a source of tin, because, like iron minerals, cassiterite is relatively stable. The richness of the mineralization within gossans, not just in the caps, has resulted in the majority of them being mined away, though historical records attest to their quality as an ore source (Carne 1821; De la Beche 1839 p326).

Erosion, particularly during the series of Ice Ages that came to an end c.10,000 years ago, caused cassiterite-bearing fragments to be broken off outcropping veins and transported down the valleys as scree. These eluvial deposits were known colloquially by the Cornish miners as ‘shode’ or ‘shoad’, and were most commonly found in dry shallow valleys above larger rivers. The amount of weathering undergone by the detached rock was extremely variable: the cassiterite might be totally freed, or remain

completely bound up with the gangue minerals with which it was associated in the vein (Gerrard 1987).

Further weathering broke down the shoad rock still further, and the action of water served to separate out the relatively dense cassiterite from the less dense gangue minerals. Some pebbles were relatively large: there are reports of 'fist-sized' pebbles being recovered; the great majority was gravel and fine sand. These sediments accumulated as alluvium in the valley bottoms. Subsequently the beds of tin rich material, which in general overlay the bedrock, might be covered with glacial sands or gravels, or peat deposits, some quite substantial.

The process of tin emplacement in alluvial deposits is complex, sometimes resulting in multiple beds, and beds of different thickness, but in general the heavier pebbles were deposited closer to the ore source, the lighter material carried further down the valleys towards the sea. For a discussion of the process of placer deposition see Camm and Hoskins (1984, 1985), and for the nature of such deposits see Henwood (1873/4).

As they frequently occur in places that, at the present day, have streams running through them, both types of detrital cassiterite (i.e. alluvial and eluvial) are colloquially referred to as 'stream tin'. However, the term is perhaps misleading, for the tin ore is not just present in the sands and gravels of the stream bed, but may underlie the entire valley bottom and can be many metres below the current ground surface.

With outcropping lodes, gossans, eluvial screes and alluvial placer deposits all potentially available to the miners of the past, the question of which of these were exploited, and to what extent, remains a topic for debate. Several authors (Shell 1979; Craddock & Craddock 1996; Gerrard 2000 p15) have remarked that, owing to the abundance of detrital tin ore available, Bronze Age miners would exploit only the

deposits at shallow depth: those requiring the least amount of labour to uncover. Limited exploitation of some of the richest and most easily accessible outcrops may also have occurred, although the mining away of the gossans themselves has destroyed any archaeological evidence there might have been to support the assertion.

The process of recovering cassiterite from alluvial deposits – known as 'tin streaming' or 'streamworking' – has been subjected to extensive study by Gerrard (1987, 1996). The details are beyond the scope of this work. Suffice to say that the recovery of stream tin required the digging of a pit through whatever depth of overburden was present, until the miner came down to the level of the cassiterite-rich 'tin ground', after which pebbles of ore could be gathered if such were present, or finer grained ore (i.e. sand size particles) could be separated out from the gangue using a flow of water. Washed ore concentrates were traditionally referred to as 'black tin'.

In contrast to other methods of metallurgical ore recovery this technique leaves little in the way of dateable evidence.

As the scale of tin streaming increased, so did the difficulties involved: deposits lay at ever greater depth, not just because the shallower deposits had been worked out, but because huge amounts of waste generated by streaming were washed down the valleys where they were re-deposited.

The ever-increasing demand for tin could not be met by the alluvial deposits alone, and thus underground mining began, eventually superseding, though never entirely displacing, streaming as the main means of obtaining tin ore.

The veins of ore were first accessed by small pits dug along the line of a shallow lode: lode-back mining. Later, larger openwork pits (known as 'goffens' or 'coffins' in

Cornwall, and ‘beams’ in Devon) were dug, and when even these would no longer suffice, true shaft mining became necessary (Gerrard 1987, 1997 p85).

1.3.3: Impurities in Tin Ores

Lode ores are often associated with metallic sulphides (commonly iron pyrites, arsenopyrite and chalcopyrite) and arsenides, as well as various oxides of iron, including titanic iron, and minerals containing tungsten (wolframite) and bismuth (Thibault 1908 p29, p146; Barton 1968 p130; de Jesus 1980 p51). Minerals of other metallic elements such as antimony, cobalt, lead and gold have also been reported (Pearce 1871; Rapp 1978 p62; de Jesus 1980 p51). Accessory minerals within the veins include quartz, apatite, topaz, mica, chlorite, fluorite, zirconia and tourmaline.

While all these mineral species are separate from the cassiterite, tin oxides may contain ions of iron, manganese, niobium, tantalum and titanium, which substitute for tin ions in the crystal (Rapp 1978 p62).

Although the cassiterite in alluvial deposits is far less concentrated than in a lode (Henwood 1873/4), detrital tin is generally of better quality than vein tin, for the weathering process will tend to remove contaminating minerals such as arsenopyrite. However, Earl warns against the assumption that all stream tin is ‘pure’: pebbles of cassiterite weathered only upon the surface, and containing trapped gangue within, are not uncommon (Earl 1994).

In addition, there is the difficulty that tungsten minerals, titanic iron and antimony minerals (if they are present) are not separated out from the cassiterite by alluvial processes as they have similar or higher densities than the cassiterite (Thibault 1908 p5).

1.4: Historical Background

The following sections provide an overview of the current understanding of tin smelting from prehistoric to early modern times, including details of the archaeological excavations and artefacts that have shaped that view, the occasionally contrary opinions of scholars who have studied the subject, and evidence from documentary sources where this is available. A glossary of terms is included in Appendix 1.

1.4.1: The Bronze Age (c.2500 BC to c.700 BC)

The earliest use of tin was almost certainly as a constituent of bronze, when it superseded arsenic as the element of choice for alloying with copper. Tin bronzes containing 7-10% tin first appear in the Near East around 3000 BC; by the early 3rd millennium BC they are found in Anatolia and Mesopotamia (e.g. De Ryck et al 2005), and by the late third to early second millennium BC are in use in the Mediterranean. The first tin bronze use in central Europe occurs around 2200 BC, and its appearance in Britain is similarly early. Pare (2000 p6-25) provides a summary of the evidence, gained from a vast body of chemical analyses of metallurgical assemblages, for the adoption of tin bronze in Bronze Age Europe. The availability of new data, including that obtained from lead isotope analyses, has driven a re-evaluation of theories relating to metallurgical development and the nature of the trade networks that permitted such development (e.g. Muhly 1985, 1999; Pernicka et al 2003 p143-8).

One of the major research problems in Prehistoric archaeometallurgy remains the identification of sources of the tin being used, tin mineralization being so very rare even without considering that some deposits may not have been known to ancient societies or exploitable by them.

Following the identification of traces of tin minerals in the Taurus Mountains of Turkey (Kaptan 1995) ancient mining sites at Bolkardağ (Yener and Özbal 1987; Yener, Özbal, Minzoni-Deroche et al 1989) and Kestel (Yener, Özbal, Kaptan et al 1989; Willies 1993; Earl and Özbal 1996) were proposed as potential sources of tin ore for the Near East and Anatolia in the Early Bronze Age, while nearby Göltepe was reported as a possible ore processing and smelting site (Earl and Yener 1993; Yener & Vandiver 1993a). Crucible fragments from Göltepe have been analysed using a variety of techniques (Vandiver et al 1993; Adriaens, Yener et al 1999; Laughlin and Todd 2001; Lehner et al 2009), and work has also been carried out on metalliferous residues and ores (Adriaens, Veny et al 1999; Yener 2003).

Claims of an Anatolian tin source have been contested, however, on the grounds that the evidence is unclear. Central Asia is viewed as a more likely source of tin by those who do not consider that the Anatolian deposits could have been worked effectively, and debate has been fierce (Hall and Steadman 1991; Muhly et al 1991; Pernicka et al 1992; Yener and Goodway 1992; Muhly 1993; Yener & Vandiver 1993b; Pernicka et al 2003 p170-1).

McGeehan-Liritzis and Taylor (1987) draw attention to minor cassiterite deposits in Serbia, described in greater detail by Durman (1997), and although there is no evidence the deposits have been exploited their location is seen as suggestive by these authors, who cite rare instances of early (pre-2000 BC) tin bronze use in the Balkans and the Aegean. Analysis of Early Bronze Age metalwork by McGeehan-Liritzis and Gale (1988 p199-225) include artefacts from Sitagroi, Greece, which the authors claim may represent the earliest use of tin in copper alloys in the Aegean.

The numerous tin bronze artefacts associated with the Únetiče (Aunjetitz) Culture of central Europe have been taken as an indication that tin was readily available in this area, suggesting that the tin deposits of the Erzgebirge region may have been exploited. The viability of these deposits as an ore source in prehistory has been debated (Dayton 1971 p57; Muhly and Wertime 1973; Penhallurick 1986 p61; Taylor 1983), and at present there is no evidence for Bronze Age mining in the Erzgebirge (Bartelheim et al 1998). Lead isotope analysis of ores and artefacts from this region has offered no support for the theory (Neiderschlag et al 2003).

Tin bronzes dating to the mid third millennium BC are known from northern Spain, although usage is very limited until the middle of the second millennium BC (Pare 2000 p22-3). Excavations at El Cerro de San Cristobal, Logrosan, have revealed the remains of Bronze Age tin mines and smelting sites (Rodríguez Díaz et al 2001).

Having considered the evidence for possible sources of tin ore, the next question concerns the form in which cassiterite was utilized. In comparison to the quantity of bronze in use in prehistoric Europe, the number of pure tin artefacts that have been discovered is relatively small. Taken together with the almost total absence of tin smelting slag in the archaeological record, this has led to some debate regarding the method by which tin bronze was produced. It has been suggested that this lack implies that cassiterite was added directly to molten copper to form bronze (Charles 1978; Tylecote 1987, 36-7). Others, however, argue that not only is this not an effective way of producing a bronze containing more than 1% tin, the very consistent percentages of tin in bronzes could only have been achieved through the addition of carefully controlled amounts of metallic tin to copper (Maddin et al 1977; Muhly 1985; Gale et al 1985 p155).

That separate smelting of cassiterite did occur, at least under some circumstances, is demonstrated by the existence of the small number of tin metal artefacts known from Bronze Age archaeological sites (for summaries see Maddin et al 1977; Muhly 1985; Primas 1985; Rohl and Northover 1994; Merideth 1998 p20). Moreover, the close parallels between tin objects found at widely separated sites have been taken as hints of a long distance trade in tin across Europe. Examples from Britain include a segmented bead from Sutton Veny in Wiltshire (Hoare 1812 p103) which is very similar to beads in two necklaces found in central Europe, one from a bog at Exloo, Odoorn, Drenthe, in the Netherlands (Penhallurick 1986 p67) and another from a grave dating to around 2000-1800 BC at Buxheim, Bavaria (Ottoway 2001); objects from Flag Fen, Cambridgeshire, and Caldicot Castle, Gwent, are comparable to artefacts recovered from several Swiss lake settlements (Rohl and Northover 1994).

Evidence for the trade of tin in metallic form, at least by the Late Bronze Age, is provided by finds of ingots (Stos-Gale et al 1998). These include the badly corroded remains of an unknown number of tin ingots, preserved beneath a substantial cargo of copper ingots, from a shipwreck off the coast of Turkey at Cape Gelidonya, dated to c.1200 BC (Bass 1961, 1967). One hundred and sixty tin ingots, with a total mass of one tonne, and a larger number of copper ingots, were recovered from a Late Bronze Age (14th Century BC) shipwreck discovered at Ulu Burun, Turkey (Bass 1986, 1987; Bass et al 1989; Pulak 1988, 1997, 1998, 2000; Lipcsei et al 2001; Hauptmann et al 2002). Recently, a vessel dating to 900 BC, which had been carrying 27 tin ingots and 259 copper ingots, was found off the coast of Salcombe, Devon (Northover forthcoming). Northover believes that the copper, and probably the tin, from this latter wreck were being imported in from all over Europe rather than being from single source.

Attempts have been made to identify sources of Bronze Age tin objects through their chemical signatures. A comparison was made of the lead isotope ratios of the Ulu Burun tin ingots with isotopic data from ores deriving from the Erzgebirge, but no match was found (Clayton, Gale et al 2002). Determinations of lead isotope ratios for finished artefacts made of tin metal are presented in Rohl and Northover 1994, but no conclusions are drawn regarding a source.

Attempts to use tin isotope analysis (by the thermal ionization mass spectrometry (TIMS) method) to relate metals in artefacts to ore sources were initially not promising (Gale 1997; Begemann et al 1999; Yi et al 1999; Nowell et al 2002), but with the recent introduction of Micromass Iso-Probe MC-ICP-MS tin isotopes may yet yield useful results (Clayton, Andersson et al 2002; Gillis & Clayton 2008; Haustein et al 2010).

Rapp et al (1999) have used neutron activation analysis to try distinguishing tin ores from different deposits by their trace element associations, and report promising results. This work also expands on earlier studies (Rapp 1978), exploring how the technique might be applied to smelted tin.

Attempts to use electron probe microanalysis (EMPA) to identify diagnostic impurities in tin metal objects from Flag Fen proved unsuccessful (Rohl and Northover 1994). Subsequently, Northover (1999) has compared the trace element compositions of the Flag Fen tin objects, as determined by ICP-MS, with parallel artefacts from a contemporary site at Hauterive-Champréveyres, Switzerland, concluding that while the sets of objects had different metallurgical histories, the data were inconclusive regarding whether they originally derived from same geological source.

In the same work, Northover discusses the use of proton induced X-ray emission (PIXE) microprobe analysis to study intermetallic inclusions in tin artefacts, which could potentially provide information about their melting history.

Comprehensive analysis of British metalwork has shown that tin bronze came into use relatively early, about 2200 BC (e.g. Needham et al 1989; Needham 1996), and the rarity of tin ore in Europe would have meant that the extremely rich deposits of cassiterite in Devon and Cornwall would have been of great economic value in facilitating the production of tin bronze.

It is therefore useful to begin by considering the evidence for ore extraction in southwest Britain.

Shell (1979) suggests that Bronze Age streamers are likely only to have worked the shallowest and richest tin deposits, it being unnecessary in the virgin mining districts to spend time and labour removing more than a minimal amount of overlying material. Stream deposits consist of gravels, which could be removed with the tools available to prehistoric people: wooden shovels and antler picks of the type reported as being found occasionally in streamworks. Unfortunately, from an archaeological point of view, any streamwork opened at an early period would almost certainly have been reworked subsequently, perhaps being expanded and deepened several times, thus it is almost inevitable that Mediaeval and later ore extraction would have erased all traces of prehistoric streamworks. That said, later streamworking has provided circumstantial evidence for prehistoric ore extraction in the form of artefacts recovered from alluvial deposits, particularly in the central and western parts of Cornwall. (It should be noted, however, that a geographical bias exists owing to these areas being extensively reworked in the 18th and 19th Centuries; the same level of reworking did not occur on

Dartmoor and Bodmin Moor, so finds from these areas are comparatively scarce). Early writers and antiquarian scholars report finds of ingots, charcoal and simple hearths, tin and copper-alloy objects and mining tools – as well as items unconnected with tin extraction – some of which may date to the Bronze Age (e.g. Carew 1602 p19; Anon 1795; Jago 1814; Bray 1836, letter of 10th April 1832; Borlase 1872; Worth 1874; Hencken 1932 p89). Pearce (1983 p107-115) lists a number of finds from streamworks in her review of the Bronze Age metalwork of southwest England, and Penhallurick (1986 p173-221) provides a detailed summary of known artefacts, the majority of which, if they can be dated at all, are of Late Bronze Age date or younger.

Unfortunately, almost all the objects from streamworks are of uncertain provenance. Even in those rare cases where the circumstances of the find were noted, problems remain: firstly, areas in which the alluvial tin deposits occur have suffered intense disturbance over a protracted period, which has seriously disrupted the stratigraphy; secondly, finds may have been recovered from within the gravel and peat overlying the cassiterite deposit, which itself may never have been exposed (Shell 1979). Additionally, artefacts – particularly hoards – may have been buried in a pit that was only coincidentally above a deposit of tin ore. Only artefacts discovered lying directly upon the tinground should thus be considered as evidence that the streamwork was open, and perhaps operational, at the time the artefact was deposited. Two of the most convincing examples come from Pentewan (or Pentuan) (SX0048), where two copper alloy implements – a spearhead and a small chisel – were found lying on the tinground, 3m below the modern land surface (Stocker 1852; Shell 1979), and Perran-ar-Worthal (SW7838), where a human skeleton, believed to be of prehistoric date, was discovered in the Carnon streamworks, laid out on the tinground (Anon 1823; Henwood 1873/4; Penhallurick 1986 p194; Gerrard 2000 p15).

Dating streamworks themselves is incredibly difficult, given the fact that similar workings continued until the early modern period, but useful clues can be obtained from the stratigraphical juxtaposition of trenches with other datable surface features such as field boundaries. A tantalizing hint of such a concurrence is offered by Earl (2002): during aerial survey of Dartmoor's tin bearing areas, clusters of many small pits were noted, and it appeared that a reave (i.e. an ancient land boundary delineated by boulders) dipped down as it passed over one of these, suggesting, if the pit is indeed related to tin extraction, a very early date.

Another method that was possibly used for ore extraction is opencast working of outcrops, particularly of tin rich gossans. Unfortunately, there is no evidence for such working in the Bronze Age; if it ever occurred it would leave minimal trace which later working would in any case obliterate.

Further evidence for the exploitation of cassiterite deposits comes from finds of pebbles of alluvial tin ore during archaeological excavations of prehistoric sites at Bussow (SW5039), Caerloggas (SX01705659), Trevisker Round (SW8769) and Dean Moor (SX678653), as discussed in Section 1.2.2. Both the Trevisker and Dean Moor settlements are situated in close proximity to alluvial tin deposits, so it is entirely possible that prehistoric people were extracting ore from them; however, on a cautious note, finds of cassiterite pebbles in an area where such are a common component of the local geology does not necessarily imply subsequent metallurgical processing was carried out – there are many reasons why individual rocks might make their way into a settlement.

All the ore finds from this period are alluvial pebbles. There is no evidence for finer grained material having been collected, and no crushing stones for grinding up larger

pebbles of ore have been identified. This suggests that ore was collected in the form of relatively substantial pebbles, however it would be imprudent to dismiss other possibilities based upon such flimsy evidence as exists.

Evidence for the production and use of tin metal is also scant.

The bead found at Sutton Veny, Wiltshire (ST8941) (Hoare 1812 p103) is thought to be the earliest tin object known from Britain, and as Shell points out, when tin is used to make items of jewellery, this is 'the small scale non-functional role we can expect for a novel, scarce material, and although these finds are proof of early separate smelting of tin metal, no evidence exists in this period for the larger quantities of metallic tin necessary for alloying copper to bronze'.

The possibility that tin metal was being used in bronze is raised by a find from the Late Bronze Age hillfort at Kenidjack Castle (SW35723251), excavated by Borlase (1879-81), where a piece of tin was included in a bronze-founder's hoard (Borlase 1882, 1885; Evans 1881 p95, p119; Shell 1979; Penhallurick 1986 p213).

In addition to the ingots from the wreck at Salcombe mentioned previously (p34), there is also a possibility that some of the tin ingots (or lumps of metallic tin) that have been discovered in Devon and Cornwall are of Bronze Age date, though in most cases these finds are from unstratified contexts. Examples postulated by various authors (Tylecote 1966; Pearce 1983 p100; Gerrard 2000 p20) include finds from Penwithick (SX0256), Burngullow (SW9852), St Wenn/Landjew Farm (SW9866), Tremethack Moor (c.SW4531), Vellin Antron Farm, Mabe (SW7633) and Bigbury Bay (SX6544). Details of these and other ingots are given in the Catalogue of Tin Metal Finds. Penhallurick (1986 p225-236) provides a comprehensive and detailed study of supposedly early ingots, many of which were first described by Henwood (1873/4). Most of these ingots

are plano-convex in section, probably owing to their having been cast into a hollow in the ground rather than using a shaped mould, but some clearly have been cast into moulds. The H-shaped ingot from the Fal Estuary off St Mawes (SW8132), which was once believed to have been of great antiquity, perhaps even Late Bronze Age, is now generally thought to be of considerably more recent date, possibly Mediaeval (Penaluna 1838 Vol 2 p258; James 1863, 1871; Piggott 1978; Beagrie 1983; Tylecote 1986 p47; Penhallurick 1986 p231-3). As Northover pointed out in a communication to Penhallurick (1986 p233), at around 72 kg the ingot would have been too valuable for any single prehistoric smith to buy. It would contain enough tin to make around three quarters of a tonne of 10% tin-bronze.

It is necessary to treat historical reports of ingots with some caution, as it is likely that at least some are not true ingots at all, in the sense that they were not deliberately cast. Molten tin may be lost through the bottom of the furnace and pool beneath it, which could easily form a rough plano-convex block. Henderson (1915) believed that this was the probable origin of the Vellin Antron 'ingots'. At least some of the other finds of tin from within or beside streamworks are likely to have been formed in this way. These are often referred to by antiquarian writers as 'Jew's House tin', as from the Elizabethan period onward it became the fashion to explain smelting-related finds in terms of a semi-mythical past. (As late as the end of the 19th Century almost all old smelting places, including some that are now known to date to the Post-mediaeval period, were referred to as Jew's Houses, for the supposed involvement of the Jews with smelting up to their expulsion from England in 1290.) Examples - none dateable (they might be as recent as the 18th Century) - include 'many ingots of tin covered with the cinders of the fuel used to reduce the metal' discovered on Shirehall Moor (SX1058), near Lostwithiel; an ingot from Trenower (SW7523) in the parish of St

Martin in Meneage; an ingot from the parish of Kea (c.SW8142) found 'amongst other lumps…[possibly of tin] …accompanied with a stratum of charred wood or charcoal'; 'a mass of Jew's House tin found among the remains of an ancient furnace near the well at Tregedna' (SW7831); and ore and refined tin from the remains of a Jew's House at Lanlivery (c.SX079590) (but see also p93) (Penhallurick 1986 p228-31).

The best and earliest evidence for tin smelting in the Bronze Age comes from the excavation of the ring-banked enclosure at Caerloggas Down (SX01705659), which was probably constructed around 1500 BC (Miles 1975). No burial is associated with the enclosure, but Miles believes that it served a ritual purpose. It is not itself a smelting site, but represents secondary deposition of several artefacts relating to tin production – including the aforementioned cassiterite pebbles (see p18).

From the same context at the centre of the enclosure came a heavily corroded fragment of an Early Bronze Age dagger, found together with six pieces of dark brown glassy tin slag, each measuring approximately 2cm square and 0.5cm thick. A seventh piece of slag, apparently disturbed from its original position, was recovered from the soil above. Both slag and dagger have been subjected to extensive analysis (Biek 1978; Salter 1997). A new analysis of the Caerloggas slag will be presented in Section 3.1.

The only other piece of slag of undoubted Bronze Age date comes from Dean Moor (SX678653), previously mentioned in connection with the find of a cassiterite pebble (p17). A minute bead of unusual reddish tin slag, only 3.2mm in diameter, was discovered in the hearth of a second roundhouse at this site (Fox 1957). (References to a bead of smelted tin found at Dean Moor (Pearce 1983 p109; Penhallurick 1986 p117-8) are a misinterpretation; the globule is slag not metal.) These finds from Dean Moor comprise the only truly convincing evidence for prehistoric tinworking in Devon;

however, not all researchers are in agreement regarding its significance. The very small size of the slag globule and the fact that it occurred singly have led some to question whether it was created by deliberate smelting (Fox 1957): Shell (1979) suggests that it was more probably the result of the accidental heating of a fragment of cassiterite in the domestic hearth, though others would insist that the conditions in a domestic hearth would not be sufficiently reducing; Harris (1968 p24) dismisses the find as an accidental by-product of iron smelting, but this cannot be so if the site is Bronze Age.

Slag has also been found in a prehistoric roundhouse at Yes Tor Bottom (SX56697295) (Baring-Gould et al 1898; Worth 1940), and in two of the roundhouses at Metherel (SX66828402 and SX66978412) (Worth 1935, 1937). The slag at the latter site was supposedly associated with pebbles of stream tin, but see Section 3.2. At both sites the smelting evidence was recovered from layers containing Late Mediaeval artefacts, so alternative explanations for the presence of slag in these prehistoric roundhouses must be sought (see p427).

What is lacking from the archaeological record for this period is any evidence for a furnace or crucibles used for tin smelting. The nature of prehistoric tin smelting furnaces thus remains a matter for speculation.

Although it is possible for temperatures in an open fire to reach 800°C on a windy day, which is sufficient to smelt copper (Doonan 1994), and temperatures as high as 1000°C have been measured in experimental cremation pyres (McKinley 1997), for the successful reduction of tin oxide such temperatures must be obtained in combination with mildly reducing conditions. An enclosed cavity is thus required. There are two basic furnace forms that might have been utilized: the pit furnace and the shaft furnace. Shaft furnaces could have operated with natural or forced draught.

The pit or bowl furnace is usually presumed to be the earliest design (Pryce 1778, Tylecote 1986; Gerrard 2000 p20): this has been envisaged as a shallow pit dug in the earth, lined with clay, and then filled with charcoal and rich cassiterite. The suggestion (e.g. by Tylecote (1980b p210)) that the burning charge may have been partially covered with a lid of earth or clay has been dismissed by Northover (pers comm. Jan 2010), but a rim of clay could have been added around the pit to increase its effective depth. Smelting would take a few hours, with the temperature kept high by the use of hand-operated bellows, the air blast directed into the furnace through a pipe of baked clay. Despite the fact that such a pipe is the part of the bowl furnace most likely to be preserved, there are no tuyères recognized in the archaeological record for southwest England; however, the technology was in use for purposes other than tin smelting elsewhere in Britain from the Early Bronze Age, as demonstrated by the discovery of a tuyère from Ewanrigg, Cumbria (Bewley et al 1992).

The shaft furnace is a refinement of the pit furnace, which allows an open tap-hole and external collecting basin for the liquid tin to be incorporated into the design. The main benefit of this is that smelting can continue for longer, there being no requirement to halt the process to empty the furnace because it is full of molten metal, and thus more metal can be produced in a single smelt.

1.4.2: The Iron Age (c.700 BC to AD 43)

As iron came to supersede bronze as the material of choice for tools and weapons in the Iron Age, the need for tin as a raw material was reduced. Despite this, bronze continued to be used throughout Europe in the manufacture of decorative items and for coinage.

Tin remained a valuable and sought-after commodity in the Mediterranean world. For example, inscriptions from 5th Century BC Athens record that purchases of up to 4000 kg of tin were made when the giant Athena Promachos statue at the Acropolis was being cast (Muhly 1985 p276).

Although there are relatively few bronzes from the British Iron Age, compared to the Late Bronze Age, analysis has been carried out on artefacts including brooches, coins, horse-fittings, vessels and even musical instruments, revealing that tin contents in bronzes remained high (c.10-14%), and that around the 5th Century BC there was a shift towards lead-free bronzes (e.g. Northover 1982, 1984a, 1984b p126-45, 1987 p186-96, 1988 p223-34; Tylecote 1986 p35-7, p114; Dungworth 1996a, 1996b, 1997b). Particularly high tin contents (>20%) are found in the 'tin-money' or speculum coins of southeast England, which date to around 50 BC (Tylecote 1986 p114).

Unalloyed tin was, on rare occasions, also used for ornamentation. Finds from two Irish sites are thought to date to the Early Iron Age: a torc from Killsallagh, and armlets from Lough Gara. There is also an item described as a mount from Llangwyllog, Anglesey. Analyses of these items are presented by Tylecote (1986 p47, p50).

Pure tin objects from Cornwall include a spindle-whorl, which was a chance find from the site of the Iron Age and Romano-British cliff fort at Trevelgue (SW8363). Earlier excavations at this site, carried out in 1939, had shown that both iron smelting and

copper alloy working had taken place within the settlement, though there was no evidence for on-site tin smelting (Wright 1940; Penhallurick 1986 p200-1; Nowakowski forthcoming).

Another example of an item manufactured from tin is a La Tène torc, dating from between 400 to 200 BC, found in a bog – there is no indication that the find site was a streamwork – in an unspecified location 'near Bodmin' some time before 1864 (Penhallurick 1986 p208).

Information regarding the origin of the tin being used in Iron Age Europe comes from the works of the classical authors of Greece and, later, the Roman Empire. These literary sources are not abundant and much of the content is questionable – and it has been questioned at great length. Nonetheless, the available literary sources suggest that both Britain and Spain supplied tin, with trade shifting between the two in response to changing relationships between Mediterranean civilizations. There is no literary evidence for the exploitation of ore deposits in Brittany at this time (Cunliffe 2001 p306).

The earliest possible references to Cornish tin are contentious, depending as they do upon the identification of the islands referred to in classical texts as the Cassiterides, the first mention of which comes from Herodotus (Book III Ch 115), writing around 450 BC: 'Of that part of Europe nearest the west, I am not able to speak with certainty… Neither am I better acquainted with the islands called the Cassiterides, from which we are said to have our tin…. It is nevertheless certain that… our tin [is] brought from those extreme regions' (Herodotus Book III Ch 115, translation from Smith 1863).

Strabo (c.54 BC to c.24 AD) (Book III, Ch5, Part 11) refers to the Cassiterides several times in his 17 volumes on geography, but implies that they are located near Iberia [Spain].

In his *Natural History*, Pliny the Elder (AD 23-79) says: 'Opposite to Celtiberia [Spain] are a number of islands, by the Greeks called Cassiterides, in consequence of their abounding in tin' (Book IV, Ch 36, translation from Bostock & Riley 1855). In an earlier passage concerning 'white lead' (i.e. tin), Pliny stated: '…there is a fabulous story told of [the Greeks] going in quest of it to the islands of the Atlantic (see p47)... It is now known that it is a production of Lusitania [Portugal] and Gallaecia [Spain] (Book XXXIV, Ch 47)'.

Diodorus Siculus, writing c.8 BC, clearly states his belief that the Cassiterides were Spanish: 'Tin also occurs in many regions of Iberia…there are many mines in the country above Lusitania and on the islets which lie off Iberia out in the ocean and are called because of that fact the Cassiterides' (Diodorus Siculus V, XXXVIII, 4, translation by Oldfather 1961-7 Vol 3 p203).

Despite the strong suggestion that all these works speak of a Spanish source for tin, historically there has been a keenness to identify the Cassiterides with Cornwall. The reference to islands with deposits of tin, and the obvious lack of such off the Atlantic coast, led in particular to the suggestion that the Cassiterides could be the Isles of Scilly (e.g. Polwhele 1803-8 Vol 3 p50-9). However, the geography and geology of Scilly make this quite unlikely: throughout the prehistoric period when sea level was lower, the Isles of Scilly were a single island; secondly, the quantity of cassiterite present on the islands is extremely small, and would not seem recoverable in any viable amounts (Penhallurick 1986 p121).

Two and a half millennia on, historians are no better acquainted with the Cassiterides than was Herodotus, and the texts that mention them cannot be taken as reliable evidence for the exploitation of British tin. For a discussion of the subject see Smith (1863) and Ramin (1965).

However, there is good reason to believe that trade links did exist between Cornwall and the Mediterranean. Spanish tin deposits may have become inaccessible to the Mediterranean civilizations following the blockade of the Straits of Gibraltar by the Carthaginians from the end of the 6th Century BC (a situation which continued up to the Roman conquest of 206 BC), leading to an interest in alternative sources (Clark 1952 p277).

When Pliny (Natural History Book IV, Ch 30, translation from Bostock & Riley 1855) wrote, 'Timaeus the historian says that an island called Mictis is within six days' sail of Britannia, in which white lead [tin] is found' his geography may have been suspect, but if Mictis can be equated with Ictis (see p48), which later writers make clear lay off the British coast, this suggests that tin was exported from Britain in Timaeus' time (c.352 – c.256 BC). Timaeus himself is believed to have based his account of Britain on the work of Pytheas of Massalia, who journeyed to the tin producing areas of Britain in about 330 BC. The city of Massalia (Marseilles), then under Greek control, offered a convenient trade route, via the Rhône, to Brittany and Britain (Cunliffe 2001 p305).

Less ambiguous evidence for the exploitation of British tin is found in texts dating from later in the pre-Roman Iron Age. While Julius Caesar's report of Britain in *De Bella Gallico* (Book V, 12), written c.40 BC, clearly contains some inaccuracies, he nonetheless states: 'The provinces remote from the sea produce tin…' (Translation from Smith 1863 p55).

Some thirty years later, Diodorus Siculus (V, XXXVIII, 4) wrote 'tin is brought in large quantities also from the island of Britain across to Gaul'. He also gave the clearest account of the tin trade in Britain of any classical author: 'The inhabitants of Britain who dwell about the promontory known as Belerium [alternatively 'Belerion' or 'Bolerion', i.e. western Cornwall] are especially hospitable to strangers and have adopted a civilized manner of life because of their intercourse with merchants of other peoples. They it is who work the tin, treating the bed which bears it in an ingenious manner. The bed is of rock, but contains earthy interstices, along which they cut a gallery. Then they work the tin into pieces the shape of knucklebones [*astragaloi* in the original text] and convey it to an island which lies off Britain and is called Ictis; for at the time of ebb tide the space between this island and the mainland is dry and they can take the tin in large quantities over to the island on their wagons… On the island of Ictis the merchants purchase the tin of the natives, and carry it from there across the strait to Galatia or Gaul; and finally, making their way on foot through Gaul for some thirty days, they bring their wares on horseback to the mouth of the river Rhône' (Diodorus Siculus V, XXII, 2, translation by Oldfather 1961-7 Vol 3 p201).

Though it is it is unlikely that Ictis was the sole place from which tin was exported, and the location of a trading centre tells us little about where and by whom tin was actually produced, debate about the identity of Ictis has been intense. Around a dozen different locations have been suggested, including the Isles of Scilly, Bigbury Bay, the Mount Batten promontory at Plymouth, the Isle of Wight (Roman Vectis) and St Michael's Mount (Leifchild 1855 p195; Edmonds 1849; James 1871; Laing 1968; Clarke 1971; Maxwell 1972; Gaskell-Brown & Hugo 1983; Cunliffe 1983a, 1983b, 1988; Penhallurick 1986 p143-6; Anon 1993; Fox 1995, 1996).

Diodorus' writing provides information regarding trade routes and also hints at the method of extraction used to obtain tin ore, which appears to be by pits and shafts dug into alluvial deposits. It also appears to offer some indication of the types of ingots being cast; however, the word *astragaloi* can be translated either as 'knucklebones', as per Oldfather (1961-7 Vol 3 p201), suggesting a sub-rectangular ingot, or 'dice' (for which purpose knucklebones were apparently used) suggesting small cubic ingots; 'cast into cubes' is an alternative translation (Leifchild 1855 p194). Moreover, the same word may be used for both size and shape, although as Penhallurick (1986 p142) points out, 'cast into the *shape* of knucklebones' seems a more sensible translation given that no very small ingots are known. (The 'small lumps of melted tin, two inches square and under' of uncertain date found in a streamworks at St Stephen in Brannel (SW9350) (Borlase 1758 p163) are more likely to be dribbles of tin escaped from a furnace than ingots.) Another school of thought regarding *astragaloi* is that it was a general term, such as is 'pigs' today (Penhallurick 1986 p142).

The H-shaped ingot from St Mawes (SW8132) is often referred to as astragaloid, and much has been made of the fact that this shape would facilitate transportation by pack-horse, while the ingot's slightly curved base would allow it to fit snugly in the bottom of a small boat, just as Diodorus Siculus describes (James 1863; Hatcher 1973 p12; Pearce 1983 p114). While this particular ingot is probably too large to be early, that is not to say that early H-shaped ingots are unknown: amongst the crudely cast, mainly plano-convex ingots found in Bigbury Bay (SX6544) were two that were H-shaped (Anon 1993; Fox 1995, 1996).

Despite Diodorus Siculus' apparent reference to the working of alluvial tin deposits, archaeological evidence for streaming is, unfortunately, very slight. There are no

artefacts of Iron Age date known from Dartmoor streamworks (Greeves 1981b), and in Cornwall the only recorded find is a La Tène fibula-type brooch from Red Moor (or Redmore) (SX0761) (Evans 1881 p400). The note that accompanied the brooch when it was handed to the Ashmolean Museum, apparently written by its original owner, states: 'Found at Redmore, St Austell, in Cornwall under 6ft of peat and 20 in. of river gravel. Beneath the sand lay another deposit of peat, 2½ feet in thickness, which had been partially cut as fuel. Mixed with the cut blocks of this second peat deposit were the remains of a smelting hearth and pieces of tin slag' (Leeds 1927; Penhallurick 1986 p197). The brooch thus appears to have been lying not on the tin ground but on, or within, a layer of peat. It is difficult to explain how this layer, and the artefact it contained, came to be overlain by a layer of river gravel save by deposition of material excavated by streamers, which did not necessarily occur at the time the brooch was lost. More peat must have subsequently built up over the top of the gravel.

It is not possible to say whether the associated smelting hearth and pieces of slag are contemporary with the brooch. The depth at which the slag was deposited may indicate an early date, allowing for the time taken for the upper layer of peat to accumulate, but this cannot be ascertained. No sample of the slag appears to have been collected.

Examples of tin ore and smelted tin metal are equally poorly represented in the archaeological record for this period. Cassiterite pebbles have been found at Chysauster (SW472350) and St Mawgan in Pyder (SW87356562), while metallic tin has been reported from Chysauster, Porthmeor (SW5236) and St Mawgan in Pyder. (Tin has also been found at Chûn Castle (SW40503395), but while the settlement may be Iron Age, the metal find probably dates to a later period; this site is considered in Section 1.4.4.) Evidence for smelting at Iron Age sites is also scant. Structures that may be interpreted

as some manner of furnace have been reported from two sites: Porthmeor and Castallack (SW4425) (see p52).

Among the finds from the excavation of the settlement at Chysauster (SW472350) (Hencken 1933) was a single large (250g) pebble of rich alluvial tin ore, which came from House 5. This appeared to have been used as a hammer stone as one surface was worn flat. A very small quantity of iron slag and some limonite that could potentially have been used as ore was also discovered in the same building. House 6 (as referred to by Hencken) had previously been cleared by Borlase, who investigated the site in 1873 (Borlase 1885). A 'piece of metal' containing 90% tin was found, but further details were not provided. A tin-glazed pot was found in House 3.

Metallic tin, a piece of what was referred to as 'dubious slag', and a possible smelting hearth were discovered at the settlement of Porthmeor (SW5236), excavated in 1935 (Anon 1936; Hirst 1937).

A single small piece of tin, size unspecified, came from the upper level of House 2, while from House 1 came another similar piece, heavily re-oxidized and weighing 1.08 kg (Penhallurick 1986 p214).

Situated at one end of House 1 was a feature described as 'a smelting hearth with part of a domed top found in position' (Anon 1936); Hirst (1937) suggested it might be a cupellation furnace.

In a corner near this hearth, was a single piece of some slag-like material; unfortunately its nature remains unclear, the report describing it only as 'unidentified slag'. Elsewhere at the site a certain amount of limonite and several other pieces of slag (not examined at the time) were also found. To judge by the appearance of material in store

at the Royal Cornwall Museum, Truro, which was examined by the present author in July 1993, this is probably iron slag.

Close to Castallack Farm (SW4425), there was discovered in 1866 a subterranean passage or 'fogou', which was excavated by Blight (Blight 1867). Blight remarked that the tenant of the estate had, whilst digging into the meadow at some earlier time, discovered 'well defined square pits, and traces of some kind of primitive furnace, or smelting place, known in Cornwall as a Jew's House'. These were situated some 27 to 36m from the fogou. No further details were recorded and it is not clear what form the pits or furnace took. Their proximity to the Iron Age remains may have been coincidence. (It is perhaps worth noting that square pits, known as buddles, were used for washing the ore prior to smelting in the Medieval and Post-medieval periods.) No evidence for tinworking was found in either the fogou, or the nearby Iron Age settlement known as the Roundago of Castallack, also examined by Blight (Blight 1865).

Excavations carried out in 1948-49 at the settlement known as Carloggas Camp, near St Mawgan in Pydar (SW87356562), close to the rich alluvial deposits of the Lanherne valley, indicate that the first phase of occupation, which dates to between AD 25 and 70, included a smelter's or founder's workshop (Threipland 1956). Finds include a cassiterite pebble, droplets of bronze, scrap bronze, charcoal, crucible fragments and a lump of a tin rich material (referred to as slag in the original report, but more likely partially reduced ore or highly corroded tin metal (Tylecote 1962 p65, 1978, 1986)).

Taken overall, documentary sources and archaeological finds all offer hints that the tin deposits of southwest England were being exploited during the pre-Roman Iron Age. Finds from settlement sites attest to the availability of tin for use in fashioning tin metal

objects, and probably as a raw material for alloying with copper; evidence for primary smelting is lacking, however.

1.4.3: The Romano-British Period (AD 43 to AD 450)

The Roman Empire utilized tin in a variety of ways. It was alloyed with copper, to make bronze, which was used for household items, in the fashioning of armour and other military equipment (e.g. Jackson 1984), for jewellery (e.g Bayley and Butcher 2004), for cast sculptures, and in coins (e.g. Cope et al 1997). Compositional analyses of Romano-British copper-alloy artefacts, including bronzes, are presented in a number of works including Tylecote (1986 p35-7, 1992 p72), Dungworth (1997a (summary of previous analyses), 1997b) and Bayley and Butcher (2004).

Tin was also alloyed with lead, to form pewter. Roman period pewter is mainly concentrated in Britain, where it was used for tableware, items of personal ornament, and more exotic objects such as curse tablets. Several hundred pewter artefacts have been analysed (e.g. Gowland 1898, Smythe 1937, Liversidge 1959, Tylecote 1986 p50, Hughes 1980; Pollard 1983; Earwood et al 2001). While there are few examples of pewter artefacts dating to before c.250 AD, in Britain the manufacture and use of pewter became increasingly common from the 3rd Century onward, such that the pewter industry grew to be by far the greatest consumer of tin in Roman Britain (Beagrie 1989; Lee 2009).

Although pewter artefacts of Roman date have been found in Europe, it is unclear how these finds relate to the Romano-British pewter industry, if they do, or whether some are of continental manufacture (Beagrie 1989).

Less commonly, tin was used as a material in its own right, for example in coins: a hoard of 700 tin denarii was found in Lyon, France (Lenormant 1878 p213); other tin coins are known from Cordoba in Spain (Bromehead 1940) and from Kirkintilloch and Bar Hill situated on the Antonine Wall in Scotland (Mattingly 1932; Abdy 2002).

Other artefacts of pure tin known from Britain include a button from Housesteads, Northumbria (Smythe 1937), a dish from Appleshaw in Hampshire (Gowland 1898), a tin bowl (possibly of Roman date) found on Fowey Moor in Cornwall (Croft-Andrew 1936) and a hand-beaten plaque (95% pure tin) from Killigrew Round, St Erme, Cornwall (Esmonde-Cleary 1998). Other items of tin, mostly ornamental in nature, are listed in Penhallurick (1986 p195, p219-21).

Tin was occasionally used as a decorative coating on copper-alloy objects, such as the mirror found at Upper Thames Street, London (Burnham et al 1996). Tinning is discussed in Northover et al (1991).

Tin in its oxide form appears to have been used as a pigment, for example in cosmetics: analysis showed it was an ingredient of the cream contained in a tin canister discovered during excavations of a mid-2nd Century Roman temple precinct in Southwark, London in 2003 (Anon 2003; Evershed et al 2004).

Perhaps surprisingly, there is very little information pertaining to the origin of the tin used by the Romans, but Iberia, Britain and possibly Brittany - Edmonsdon (1989) cites a survey by Galliou (1982 p21-32) that has provided evidence for the exploitation of the tin deposits of Brittany - are believed to have supplied the Empire's needs.

It is known from literary sources that the Romans obtained other metals from the rich and varied mineral deposits of Iberia; those same sources are less concerned with tin, but it is not unreasonable to assume that the rich cassiterite deposits of Spain and Portugal were also exploited, particularly during the 1st and 2nd Centuries AD. Surveys of the Iberian tin bearing areas have produced archaeological evidence for the extraction of cassiterite (Edmondson 1987, 1989; Merideth 1998), and Merideth

(1998 p92-4, p143-9) presents an analysis of tin smelting slag from Torre Romana Centumcellas in Portugal (which, with its crystalline microstructure and high tantalum and niobium content, is of very different character to the slags of southwest England).

From the 3rd Century AD, there appears to have been a decline in production from the Iberian mines, possibly as a result of the increasing threat of attack from barbarian raiders; nevertheless, it is now believed that the area's tin deposits continued to be worked on a small-scale throughout the Roman period and beyond (Edmondson 1989).

To what extent the Romans exerted control over tin production in Britain is not known. If any efforts were made to develop the industry there, they have gone unremarked by the writers of the Imperial period (Hatcher 1973 p13). The consensus is that native communities west of Exeter were largely self-administering (e.g. Penhallurick 1986 p210; Quinnell 1986; Gerrard 2000 p22). Evidence of Roman occupation in Cornwall is minimal; while new roads were constructed, no administrative centres or mining towns such as are seen elsewhere in Britain appear, and only one Roman fort was erected.

It is generally believed that British tin production was conducted only on a small-scale during the first two centuries AD: Caesar's wars in Brittany in the 1st Century BC may have disrupted the British tin trade, and subsequently the Iberian mines fulfilled the Empire's needs. However, falling production from the Iberian mines appears to have fuelled an increase in British output. A summary of the arguments relating to the shifting fortunes of the Iberian and British tin industries is presented in Hammersen (2007 page 93-6).

In fact, there is archaeological evidence for the extraction of alluvial cassiterite in Britain throughout the Roman period, both in the form of finds from streamworks and the appearance of pebbles of stream tin in settlements.

One of the streamworks to have yielded up artefacts dating to the 1st Century AD is at Boscarne (SX039675), situated quite close to the settlement at Carloggas, St Mawgan in Pydar (Gerrard 1986 p41). Penhallurick (1986 p173-221) gives details of many other objects of Romano-British date recovered from Cornish streamworks, including jewellery, tin and pewter vessels, and coins. There are no artefacts of this period from Devon's streamworks, although this does not necessarily mean these were unused (see p36) (Greeves 1981b). It has been suggested by Thorndycraft and co-workers, who carried out analysis of sediments from the River Erme in Devon, that exploitation of the deposits in the valley bottom may have begun in the late Roman period (Thorndycraft et al 2004).

The possibility that mining was also carried out may be raised. Gerrard (2000 p22) notes (with reservations) that 'an adit at Baldue (SW7742) was believed by Hunt to be Roman because of 'the perfection of the arch formed and the good masonry of squared stones of which it was constructed'.' Meanwhile, Penhallurick (1986 p212) draws attention to the extreme paucity of finds from the streamworks of Penwith, suggesting that this may be due to a preference for tin ore taken from the easily accessible veins that outcrop in the far west of Cornwall.

Further hints for the use of vein material come from Trethurgy Round (SX03475564), a Late Roman period defensive enclosure discovered in 1972 (Miles 1973; Quinnell 2004 p75). The site is close to alluvial tin deposits and three cassiterite pebbles were

discovered, in three separate structures, during the course of the excavations; but, in addition, two areas yielded fragments of schorl, a mineral often associated with cassiterite in lodes, which has been interpreted as possible evidence either for the exploitation of the veins that outcrop some way to the north of the site, or for the collection and use of shoad tin ore.

Finds of pebbles of alluvial cassiterite from two other Romano-British settlements are recorded. A single specimen came from within the enclosure at Castle Gotha (SX030496) near St Austell, occupied during the first two centuries AD, where clear evidence for bronze-working was found (Saunders 1960-1).

Two large pebbles of stream tin were found at Carn Euny (also known as Chapel Euny), Sancreed (SW396294), a habitation site with a number of subterranean passages excavated between 1863 and 1868 (Borlase 1870 p167). Borlase also reported the find of a piece of 'fused tin' in the long chamber of the fogou (Borlase 1872 p260, 1873).

The conclusion drawn from all these excavations is that smelting of tin did not actually take place at the settlements themselves, but as with smelting in earlier periods was carried out beside the streamworks.

Several ingots can - more or less convincingly - be assigned to the period. The tin metal from excavations at Carn Euny has already been mentioned.

The more recent excavation at Trethurgy Round (Miles 1973; Quinnell 2004) revealed a rough oval plano-convex tin ingot, which was very corroded, to the extent that its weight (originally estimated from the flakes accompanying it at about 13 kg) had reduced to just over 7 kg (Quinnell 2004 p76). In all respects, this ingot is

indistinguishable from examples believed to be Bronze Age; only the context of its burial identifies it as Romano-British. Bayley, who carried out XRF analysis on the ingot, suggests that the tin, which is now partially re-oxidized, is comparable to that in other ingots, the compositions of which have been given by Tylecote (1962 p66), i.e. 99% tin or better (Quinnell 2004 p73).

Another plano-convex ingot came from a circular building just below the high tide line at Par Beach (SV932153) in the Scilly Isles. This roundhouse, which also contained 3rd or 4th Century AD pottery, was excavated in 1948 (O'Neil 1949, 1961 p10). (O'Neil mentions finding pieces of cassiterite or tin ore: in this he may have been referring to a pebble that resembled stream tin, which analysis subsequently determined was not cassiterite (Penhallurick 1986 p121); otherwise the statement may have been prompted by the highly corroded state of the ingot.) Tylecote (1978) describes a thin plano-convex ingot crusted with a dense corrosion product, but with a highly ductile metal core indicating highly pure metal. No drawing was made, nor were its dimensions recorded, but the probable remains of this object (consisting of 61g of corrosion product) are now in the Royal Cornwall Museum, Truro (Beagrie 1985; Penhallurick 1986 p121). Penhallurick believes that the ingot was imported from elsewhere and should not be interpreted as evidence of tin smelting in the Scilly Isles; the same should be borne in mind for all sites where ingots are discovered without other evidence attesting to smelting having been carried out.

A 'lump of smelted metal' found at the Romano-British walled settlement site at Goldherring, Sancreed (SW411282), is probably not contemporary with the settlement (see p99).

Other ingots believed to be Roman include two, weighing just over 10 kg each, from a streamwork in the Pentewan valley (SX0147 to SX0151), discovered in the early 18th Century. These are now lost, but one was drawn by Borlase (1758 p163), who also gave a brief description. The ingots are unusual in that they have a looped handle on one short end.

All other known examples of handled ingots date to the Roman period, specifically the 1st Century AD; parallels include ingots from two wrecks, one found off Port Vendres in the south of France, which had 14 ingots with weights in the range of 3.12 to 8.75 kg, and another off Cap Bellevista on the coast of Sardinia, which yielded 32 ingots with weights of 4 to 5 kg each (Beagrie 1985; Penhallurick 1986 p108). It has been suggested that the Cornish ingots are copies of a design commonly used in Iberia.

In the Royal Cornwall Museum at Truro is a wedge- or boat-shaped ingot weighing 17.8 kg, with a convex base the texture of which suggests it was cast into a granite mould. This was found at the Barton of Carnanton (SW886640) some time around 1819, 'contiguous to what is usually called a Jew's House' (Anon 1821; Hogg 1825 p75 [sometimes attributed to Michell]; Poole 1865). The ingot has been examined by several researchers (Way 1859; Haverfield 1894, 1900, 1903 p249; Smythe 1937; Warner 1967; Beagrie 1985). Its flat top surface has upon it some faint impressions, hammered into the tin when cold, which even in the 19th Century were hard to interpret due to blistering of the metal. However, Haverfield claimed to see one stamp that was a helmeted head in profile, with a small shield or buckler at its base, and another that consisted of four letters: two unclear, originally thought to be IE or IF, followed by two Ns run together, but later interpreted as DDNN, a formula known

from 3rd and 4th Century silver ingots, meaning *Dominorum Nostrorum*. On the basis of the assumed Latin inscription, and the fact that the helmet resembled 3rd /4th Century Roman helmets, Haverfield proposed a Roman date for the ingot.

The stamps are now all but indecipherable, and their existence – in addition to their interpretation – has been questioned by some (Tylecote 1962 p67, 1966). Smythe saw only a staple-shaped stamp, repeated six times over (Smythe 1937). Others re-examining the ingot more recently have concluded that IENN, impressed twice, is the more likely series of letters, owing to the lack of space for DD, while the helmet stamp was impressed a total of seven times (Warner 1967; Beagrie 1985; Penhallurick 1986 p205).

Smythe's analysis of the crust showed that, when reduced to metal, the tin was extremely pure, containing 99.9% tin (Smythe 1937).

The place in which the ingot was found is still known locally as Jew's House Meadow (Penhallurick 1986 p205) and around 1821 when the head of a spring was cleared, a vessel containing several hundred coins of Elizabeth I through to Charles II was discovered 'a few yards' from the ingot's find spot (Anon 1821), which casts into question the age of the smelting site, and hence that of the ingot. Of this building nothing apparently remains.

An ingot was found about 200m from Castle Zen (c.SW915395) in the parish of Veryan (Burnard 1888). Its discovery is reported as being made some years before 1832, and is described as 'a block of tin of a singular form, which has on it an inscription in Roman letters' (Hawkins 1832). There is no further information concerning either the form of the ingot or the nature of the inscription, and as the

ingot was not preserved, it is not possible to say whether or not it could have been Roman.

A corroded plano-convex ingot, which originally weighed 3.2 kg, is described as having come 'from Boscarne' but the circumstances of its discovery are not recorded. This may be associated with the 'Jew's House' at Ruthern Bridge (SX013669) (Penhallurick 1986 p210), which it has been suggested may be Romano-British based upon its proximity to the Roman camp at Nanstallon (Tregear) (SX034673), and the fact that several coins of Vespasian were found in the nearby streamwork. The Jew's House was described by the anonymous 'Stannator' in 1828 only as six furnaces resembling straw beehives set in a line, each of a size that would 'contain about 3 gallons of water' (Anon 1828). The furnaces thus appear to have been domed, and – if the Stannator's estimate of volume is correct – relatively small (c.18,000 cm^3 cf. c.450,000 cm^3 for the Post-mediaeval furnace at Lower Merrivale (SX55277535)).

Finally, from the remains of another Jew's House at Trereife (SW455294), near Penzance, came a well-preserved rectangular ingot, weighing 13.4kg and measuring 42 x 20 x 5cm. Workmen discovered an inverted cone-shaped cavity cut into a bank of clay, and at the top of that cavity atop the earth and rubble that filled it, sat the ingot. This find was first described in 1846 by Le Grice who thought that it dated to the Roman period (Le Grice 1846). Subsequently it has been suggested that the ingot is Mediaeval (Haverfield 1900), or even later: cast in relief upon the surface of the ingot is an elaborate cross symbol and the letters EIC (Way 1866), which some have speculated stands for 'East India Company', thus suggesting a Post-mediaeval date (Tylecote 1966; Penhallurick 1986 p235). Analysis of this ingot has showed that the metal is 99.9% pure tin (Smythe 1937).

The reputed furnace at Trereife bears no resemblance to those at Ruthern Bridge. The unlined cavity was approximately 90cm deep with a diameter c.90cm at the top, tapering to c.30cm at the base where there was a flat stone with a border of smaller stones around it. A layer of ash covered this slab. On one side was a gully that may have admitted an air blast or allowed molten tin to escape the furnace. Gowland (1899) speculated that this structure was too large to function effectively as a tin smelting furnace blown with primitive bellows, and while it may originally have had some form of lining to reduce its internal dimensions, its nature and age must be called into question. The date of this structure is doubly contentious, being based upon the uncertain dating of the ingot, which may or may not be contemporary with the furnace in which it was found, though it is tempting to link the two. It is possible that the furnace could be Romano-British. Equally it could conceivably be associated with a defunct blowing house documented in 1739, the exact location of which is unknown (Barton 1971 p77).

The majority of the ingots discussed here conform to what is expected for the Roman period. Ingots from the Mediterranean region that have been more securely dated than the Cornish examples, suggest that a mass of less than 10 kg was typical, although larger ingots, up to 30kg, are known (Beagrie 1983). Where these ingots were smelted is not known. Other than the structures at Ruthern Bridge and Trereife – which are of dubious purpose and date – no recognizable tin smelting furnaces are extant in the archaeological record for the Romano-British period. An hour-glass shaped pit furnace at Killigrew Round, Trispen (Anon 1996-7; Esmonde-Cleary 1998; Nowakowski & Cole forthcoming), dating to the 2nd and 3rd Centuries AD was initially considered to be a possible tin smelting furnace. However, X-ray

fluorescence analysis of slag and furnace lining samples by the present author showed only trace levels of tin to be present.

Glassy tin slag that may potentially date to this period has been discovered at only one site. Three discrete concentrations of slag were discovered during excavations at the Post-medieval tin mill at Upper Merrivale (SX55197664) in 1992 (Gerrard & Greeves 1992a), in a trench dug to investigate the leat system that carried water to the mill from a reservoir on the hillside above. At the south end of the trench, furthest from the reservoir, was a large boulder, interpreted as a prehistoric boulder cairn, which had pieces of slag and worked flints, mixed in with a number of stones, piled against it on the upslope side. Just upstream of the outflow channel from the reservoir was a mound with two ditches, with more slag and worked flints in the upper parts of the feature (the lower part was not excavated).

Following the discovery of the flints and slag, a larger area was opened for excavation at the upper end of the trench. In the centre of a scatter of stones that were lying upon a buried soil surface and were thought to be from field clearance, was a discrete concentration of tin slag, amounting to several thousand small pieces. This slag was associated with a relatively unabraded fragment of pottery and more worked flints. The possibility of the pottery fragment being Romano-British was raised (Greeves 1995), but Quinnell, who examined the fragment initially, was reported to favour a Neolithic date (Gerrard & Greeves 1992a), and subsequent analysis of the material appears to support this (Greeves 2010a). If this early date is confirmed, then the pottery must, like the flints, have been disturbed by later tinners, and cannot have any connection to smelting. However, the position of the find in relation to the later mill, which is more than 30m away down a steep slope, is interesting: the likelihood

of the slag being transported there from the blowing house seems small. An analysis of slag from this area is included in Section 3.1.

Excavations in 1993 showed that there was a gully, probably prehistoric in date, situated not far from the slag scatter, and this is thought to have been an openwork for obtaining tin ore (Greeves 1993b).

1.4.4: The Dark Ages (AD 450 to AD 1000)

Evidence for tin smelting in the Dark Ages is slender and of variable quality; however, taken as a whole, it appears to indicate that production continued in the wake of the Romans' departure. There was certainly a demand for the metal: Cu-Sn alloys were in common use in Post-Roman Britain. The production of, and trade in, tin likely remained important to the economy of southwest England. Indeed, it has been suggested that one of the reasons King Alfred chose Lydford as a site for a fortified town in the 9th Century was to place himself in a position where he could exert control over the Dartmoor tin trade (Greeves & Newman 1994).

Support for continued tin production in the Dark Ages can be found in a very small number of documentary sources, which have been considered in some detail by Hatcher (1973 p13). Though described as 'inconclusive and ambiguous' by him, he attributes this to the probability that the industry responded to varying demand, with concomitant peaks and troughs in production.

The fanciful tale of John the Almsgiver (Leontius 'Vita S. Ionnis Eleemosynarii', Migne's Patrologia (Greek Series) xciv, 1625), a patriarch of Alexandria who died c.AD 616, in which a group of starving Britons gave a ship's captain tin in exchange for his cargo of grain, has been seen as circumstantial evidence for continued commerce with the Mediterranean region in the post-Roman period, but also implies that John's contemporary biographer recognized Britain as a place where tin could be sourced (Hedges 1969 p12; Hatcher 1973 p15; Penhallurick 1986 p237, p245). Tin was certainly included in the range of items transported in the 7th Century, being carried by Saxon merchants to the fairs established by the French King Dagobert (Hatcher 1973 p15; Penhallurick 1986 p240). In the 9th Century, customs regulations and travellers

tales point to British tin being imported into Russia through Germany and Austria (Hedges 1969 p89; Penhallurick 1986 p240).

Not all the documentary sources are so positive, or so clear. The fact that Aelfric, Abbot of Eynsham, specifically referred to tin as a commodity not produced in the country in which he lived around the end of the 10th Century, has been explained by considering how remote was Cornwall to his abbey in southeast England (Hatcher 1973 p17; Penahllurick 1986 p240). Equally, Hatcher (1973, p17) notes that Bede fails to list '*stannum*' in his description of the country's natural resources. Hatcher speculates that tin may have been grouped together with lead as '*plumbum*'. As Bede was probably familiar with lead, the ore being readily available in the Northern Pennines, whilst tin came only from the far southwest, it at first glance seems strange that the two metals would be grouped thus. Difficulties of translation from the Latin may provide an explanation: Hoover and Hoover in their 1950 translation of Agricola (1556 p392) argue that '*stannum*' refers to an alloy of silver and lead, while tin was usually rendered as '*plumbum candidum*' or '*plumbum album*', with the second word often being omitted (Agricola 1556 p411; Hatcher 1973 p17), such that the same word was used for both tin and lead.

The archaeological record is equally sparse in terms of artefacts relating to tin production. There is no evidence for vein mining from the period at all, but streaming does appear to have been carried out.

Gerrard, who has made an extensive study of the streamworks of Cornwall, draws attention to the work of Walker, who has examined pollen cores from disused streamworks, which slowly silt up after abandonment. One core from Colliford (SX1771) had a pollen profile suggesting that the streamwork ceased work around 600-

700 AD (Gerrard 1987). In addition, the geochemical analysis of sediments from the Erme Valley (SX6365) carried out by Thorndycraft et al (2004) suggests that streaming was carried out between the 4th and 7th Centuries.

One of the best pieces of evidence for tin streaming comes from Boscarne (SX039675), where three wooden shovels have been discovered in streamworkings; although they are not all thought to date to the same period, the one that has been radiocarbon dated gave a date between AD635 and 1045 (Penhallurick 1986 p211).

A treasure hoard, including many coins dating from between AD 757 and 901, was found buried 5m deep in a streamwork at Trewhiddle near St Austell (SX0150) (Rashleigh 1789, 1794; Hencken 1932 p262; Penhallurick 1986 p181-3; Gerrard 2000 p23). A 4th to 6th Century brooch from a streamwork somewhere near Lanivet, perhaps from Goss Moor (SW9459), was presented to Truro museum in the 1820s; another brooch, which might be post-Roman, was found with a probable 2nd Century ring at Polmassick (SW973455) in 1787 (Penhallurick 1986 p237; Gerrard 2000 p23). As with all finds from streamworks, the possibility arises that these artefacts could become buried without there being any active work in progress.

There have also been finds of ingots at two sites that are possibly of Dark Age date. Four plano-convex ingots, ranging in weight from c.0.9kg to 3.8kg, were found at Praa (or Prah) Sands (SW580279), after a storm in 1974 stripped away the dunes, revealing a soil layer filled with fragments of sub-fossil wood that was radiocarbon dated to c.AD 660 (Biek 1978, 1994; Penhallurick 1986 p234). Unfortunately, it cannot be certain whether the ingots are 7th Century or predate the inundation of the woods by the dunes (Biek 1994).

The second site is Chûn Castle (SW40503395), a hilltop fortress excavated between 1925 and 1930 by Leeds (Leeds 1927, 1931). The settlement consisted of a circular surrounding wall and ditch enclosing eleven or twelve rounded or sub-rectangular chambers built up against the outer wall. Leeds assigned the settlement to the Iron Age, but suspected some of the buildings may have been secondary to the defences, and Thomas' re-evaluation of the ceramics extends the occupation date for some parts of the site to the post-Roman period: the 5th or 6th Centuries AD, but perhaps as late as the 8th Century (Thomas 1956).

Artefacts relating to tin smelting appear to be associated with the later phase. A flattened disc-shaped mass of oxidized tin weighing c.5kg (dimensions of this object given by Tylecote (1966, 1978) are erroneous), along with pottery, came from below the paved floor of a house situated c.3m to the east of a well (Leeds 1927). Leeds describes this find both as 'a large block of tin ore' and 'a large oval cake of tin slag', but notes a metallic core consisting of laminated layers of tin with interstitial patches of an antimony compound (Leeds 1927). Subsequently this material was examined by Tylecote, who believes it to be a corroded ingot of metallic tin (Tylecote 1978).

Tylecote (1966, 1978) also refers to another, smaller piece of tin found close by, but no independent record of this can be found.

About 1m to the south of the well was another structure, which Leeds interpreted as a furnace. This feature was associated with sherds of amphorae that, according to Thomas, have only been found in post-Roman contexts in Britain (Thomas 1956). (Penhallurick (1986 p213) mistakenly states that, 'The furnace, in hut C, was associated with pottery bearing on its base the marks of chopped grass, a type common throughout post-Roman Cornwall until the 11th Century, as well as sherds of amphorae imported

during the years 500 to 700'. Hut C contained the grass-marked ware, which Thomas dates to AD 500-700, but the amphorae sherds came from the area around and within the 'furnace', which is a separate structure (A), at the opposite side of the site to hut C.)

Roughly built of irregular blocks and earth, the so-called furnace measured 3m, east to west, and 1.5m, north to south (exterior dimensions). Leeds estimated the original height at 45cm. Three fire-holes, c.20cm across, were situated in a line east to west, each with its own flue leading out to the south, while a fourth flue was common to all three fire-holes, connecting them along the east-west axis and emerging from the east side of the eastern-most fire-hole. Black soil, rich with charcoal, filled all the fire-holes and flues. Abundant charcoal, mainly heather roots and gorse, was also mixed with the soil around the furnace on the side where the flues emerged (Leeds 1927).

Leeds also reported that 'a small quantity of slag came from in and around the furnace'. Unfortunately, he did not identify the slag further, but does state elsewhere in his report that slag found in the adjoining hut, where the ingot was discovered, was iron slag.

Situated at the southwest corner of the furnace, there was what appeared to be a trough, constructed from slabs set into the earth; this measured c.45cm x 25cm, its edges varying in height between 5cm and 20cm. Leeds does not speculate upon the purpose of this trough.

It appears possible that the structure was some manner of smelting furnace, as Leeds interpreted it to be, which was either constructed in the post-Roman period or was an earlier structure re-used at that time. Initially, Tylecote envisaged the structure as a series of three small furnaces, with the flues being used to provide a supply of air to a mix of ore and charcoal placed within the shaft-like 'fire-holes' (Tylecote 1962 p64), but later reconsidered, and expressed doubts that the structure operated as a furnace,

suggesting instead that it may have been a crucible-melting furnace (Tylecote 1986 p43).

There is, in the museum at Truro, a square piece of granite, measuring 15cm across and standing 10cm high, which has a circular cavity hollowed out of one face. This object is alleged to have come from Chûn Castle, although the date and circumstances of its finding are unknown. Leeds likens it to other similar specimens that have been discovered in Cornwall, and implies that it may be a mould (Leeds 1927).

Another potential Dark Age smelting site, also disputed, is Week Ford in Devon (SX663723), where two Post-Mediaeval tin mills are sited. The earliest documentary reference to the mills is from 1608 (DCO London, Dartmoor Proceedings 1203-1735 fol 29), though Greeves reports finding pottery in the vicinity that may be as early as 15th Century (Greeves 1990). However, while investigating the tin mills, Earl (1989) discovered a trail of tin processing debris running down from the mills towards the river. Erosion of the riverbank had exposed an archaeological section c.1m in depth, which contained a layer of dressing tails atop peat, above this was a relatively thick layer of smelting waste including tin slag, and on top of that a thin layer of charcoal fragments. More tails and debris covered the charcoal layer.

A single piece of the charcoal was radiocarbon dated, and gave a date of between AD640 to AD800 (68%), or AD570 to AD890 (95%), which Earl interpreted as evidence that simple ore washing followed by smelting had been carried out at the site at some time during the 8th Century, long before the construction of the mills currently on the site (Earl 1990).

Greeves (Greeves 1990), however, dismisses the report, asserting that the single radiocarbon date is meaningless, even if it were possible to be certain that the slag and

charcoal were associated. It is also pointed out that the stratigraphy of the site has been severely disrupted. Newman (1993) also opines that there are insufficient grounds to accept an 8th Century date for smelting at Week Ford.

One final piece of circumstantial evidence for there having been tin working in the Dark Ages is provided by the apparently well established laws and customs relating to its extraction (Lewis 1908 p34; Pennington 1973 p9, p12, p72-3). It has been argued that Stannary Law, known to have been in effect in the Mediaeval period, predated the Norman Conquest, and perhaps even derived from a time prior to the coming of the Saxons to the southwest, since it is quite different in character from mining laws elsewhere in the country that are understood to be Anglo-Saxon. Much is made of the fact that tinners had the right to dig for tin wherever they suspected it might be found – regardless of who owned the land.

Reference is made in early documents to the antiquity of the established customs. For example, in 1198, a number of the King's officers including William de Wrotham, produced documentation in which it was stated that the tinners were to have the same freedom that they had enjoyed formerly, and mention was made of the just and ancient customs and liberties established in Devon and Cornwall (see p78). These privileges were again recognized as being ancient when they were confirmed in the first Stannary charter issued by King John in 1201 (Worth 1910).

It therefore appears that, despite the lack of firm evidence in both the archaeological and documentary records, tin production continued during the Dark Ages, and though it the quantities of tin obtained may have been relatively small, there was sufficient continuity within the industry to ensure that the rights of the tinners became so firmly

established that they withstood the considerable changes in social order occasioned by the arrival of the Normans (see Section 1.4.5).

1.4.5: The Mediaeval Period (AD 1000 to AD 1500)

1.4.5.1: Documentary Evidence for Tinworking

The evidence for tin smelting at the beginning of the Mediaeval period is no more revealing than for the preceding centuries. Several researchers have noted the absence of tin from the Domesday Book of 1086 (Williams & Martin 2003), but the reason for this omission is not known. Other mining activities elsewhere in the country were included. Burnard (1888) suggests that since tinworks were generally on marginal land not under any permanent form of management, revenue was obtained by the crown through rents paid by the miners rather than through a land tax collected annually. It is not clear from any of the documentary sources available for the early Mediaeval who would be the legal owner of the tin, but Lewis (1908 p75), who discusses the issue of ownership generally, in the context of early mining law, considers the possibility that tin was one of the metals deemed to be a royal property. In that case, it would not be included in a survey intended to determine the value of estates for taxation purposes. For a metal to be claimed as Crown property implies that the revenues derived from it were considerable, which supports the idea of a flourishing industry.

Lewis nevertheless considers the alternative: that there simply was no exploitation of tin occurring at that time, or so little as to warrant it being included in the miscellaneous revenues.

From the 12th Century onward there is unequivocal documentary evidence attesting to the fact that tin was produced in England. Tax paid by the owners of the tin was levied at the rate of 30d per thousandweight in Devon and 5s (i.e. 60d) per thousandweight in Cornwall. Tax collection was farmed (i.e. authority to collect the tax was given to an individual or group of individuals on payment of a fixed amount to the Crown), but

payments were recorded in the Pipe Rolls, a series of financial records used by the Exchequer to record Crown incomes and expenses. The first document alluding to tin that is still extant dates from 1155/6 (Hatcher 1973 p18).

Unfortunately, the data for the 12th Century is incomplete. Moreover, the sum of the farm for the period 1156-1189 appears only in Pipe Rolls relating to Devon, superficially making it appear that tin was obtained only from Devon at this time, whereas in fact the entries merely show that the individuals paying the tax were based in Devon. Production then appears to shift completely to Cornwall for 1195, then back to Devon in 1197, before the Pipe Rolls show figures for the farm of the tin in both counties between 1200 and 1214. Despite the ambiguous production figures, it is usually agreed that most tin was being obtained from Devon at this time. Lewis (1908 p43) points out that the number of witnesses giving evidence at the inquests into tin production held in 1198 was greater in Exeter, which had 26 witnesses standing, than for Launceston, with 18, and this reflects the relative importance of the two counties.

All the researchers who have studied the data from the Pipe Rolls agree that the figures for Devon may include output from some Cornish mines (Lewis 1908 p34), and vice versa. This leads to difficulties in calculating the actual mass of tin produced, because the duty in the two counties was different and it is not known what proportion of the output derived from each county. This is further exacerbated by the fact that there was a difference in the mass of the Devon and Cornwall Stannary thousandweights. (The issue of the value of the thousandweight is confused: Lewis (1908) uses a thousandweight of 1200 lbs throughout his work, making no distinction between Devon and Cornwall; Hatcher (1970 p24, 1973 p21) gives the Devon Stannary thousandweight as 1200 lbs and the Cornish Stannary thousandweight as 1000 lbs; Dr Cotton (1664),

writing about Devon, states that a hundredweight is 120 lbs, while in 1724 Kalmeter (translated Brooke 1998 p350) gives the Cornish hundredweight as 120 lbs and the Devon hundredweight as 100 lbs). The farmer's profit margin and the level of tax evasion, both unknown quantities, are also complicating factors when attempting to make this calculation (Hatcher 1973 p152).

These problems aside, the estimates produced are in broad agreement (Lewis 1908 p252-8; Hatcher 1973 p154-9). Output was initially relatively modest, estimated at about 60 tons (54.4 tonnes) per year, but it increased fivefold between 1160 and 1171, reaching 320 tons (290 tonnes) per year (Hedges 1969 p12), and continued to grow, albeit more slowly, thereafter.

English tin was in high demand at this time, for with the fall of Spain to the Moors southwest England was the sole source of the metal in Europe; the mines of Bohemia and Saxony may have been worked in a minor way prior to the 13th Century, but it is popularly believed that they were not discovered until 1240 (Hatcher 1973 p18; Brooke 1998 p333).

Quantities of tin produced in England and revenues raised upon it were recorded in a series of records known as the Coinage Rolls, beginning in the early Mediaeval period and extending through to 1837. Extracts from these records have been published by Lewis (1908 p252-8), Mitchell (1962), and Hatcher (1973 p154-9).

As Crown interest in tin production was essentially financial, the quality of the data that relates to tin output contained in Crown documents varies according to which system for collecting revenues was in place as much as it depends upon the survival of pertinent records. The system underwent various changes during the early Mediaeval

period, and the complexities of the subject have been discussed by Lewis (1908 p131-56) and Worth (1910).

In 1198, the new Lord Warden of the Stannaries, William De Wrotham, was charged with increasing revenues deriving from tin for the benefit of the Crown. An additional tax of 1 mark (i.e. 13s 4d = 160d) per thousandweight was introduced, payable on the so-called 'tin of the second smelting' (see p78). Between 1198 and 1215 the Pipe Rolls record the total number of thousandweights of tin presented for assessment for the new tax, although there is still no distinction made between tin produced in Devon and tin produced in Cornwall. Production in 1198/9 amounted to 900 thousandweights, this figure including both Devon and Cornwall Stannary thousandweights (Hatcher 1973 p20).

Separate taxation of tin of the first and second smeltings continued until 1303, when the two taxes were replaced with a single tax on the finished metal, amounting to 4s per hundredweight in Cornwall and 1s 6 ¾ d per hundredweight in Devon (Greeves 1981b). (Interestingly, the two counties continue to have different tax rates and there does not appear to have been any attempt by the Cornish tinners to remedy the discrepancy (Greeves 1992). For a discussion of this see Section 4.6.3.)

A summary of taxes levied upon tin in the Mediaeval period is presented in Table 1.1.

Documents relating to the imposition of this new tax, and the inquests that were held to investigate the workings of the tin industry, have survived. The correspondence between De Wrotham and the other Crown officials charged with this undertaking, and those to whom they reported, to whit Archbishop Hubert Walter of Canterbury, Lord Geoffrey FitzPeter (De Wrotham's predecessor), and the Barons of the Exchequer, are the earliest documents that offer more clues to the operation of the early Mediaeval tin

industry than the annual income and production figures alone. (A transcript of the original Latin correspondence is given in Lewis (1908 p233-8), Halsall (1998) provides a translation, and a partial translation is also given by Worth (1910).)

Table 1.1: Summary of Tin Tax Rates in the Mediaeval Period (A Devon Stannary thousandweight of 1200 lbs and Cornish Stannary thousandweight of 1000 lbs is assumed).

Period of Taxation	**Tax Rate in Devon**	**Tax Rate in Cornwall**
1156 - 1198	30d per thousandweight of 1200 lbs (0.025d per lb)	5s per thousandweight of 1000 lbs (0.060d per lb)
1198 - 1303	30d on tin of first smelting + 1 mark on tin of second smelting per thousandweight of 1200 lbs (0.16d per lb)	5s on tin of first smelting + 1 mark on tin of second smelting per thousandweight of 1000 lbs (0.22d per lb)
1303 onwards	Single tax of 1s 6 ¾ d per hundredweight of 120lb (0.15d per lb)	Single tax of 4s per hundredweight of 100lb (0.48d per lb)

The language used in De Wrotham's report makes it clear that the practices of the industry were long established; for example, there is reference to 'the just and ancient weight of the city of Exeter, by which anciently now and at all times the second smelting of tin was wont to be made' (…justum et antiquum pondus civitatis Exoniae per quod antiquitus et nunc et semper solebat fieri secunda funtura stagni est de tali quantitate…), while 'the first smelters of tin, and the traders of tin of the first smelting, shall have the just and ancient customs and liberties, established in Devon and Cornwall' (…de stagno primi fusores et de stagno primae funturae mercantores habent Justas et antiquas consuetudines et libertates in Devonia et Cornubia constitutas) (Worth 1910).

The second point to arise is that these references to tin of both the *first smelting* and *second smelting* imply that the production of tin metal was a two-stage process. Consideration of the De Wrotham documents has led Greeves (1981b), for example, to

suggest that the first smelting occurred close to the place where the tin ore was raised, producing an ingot of tin, and the second 'smelting' was a re-melting, i.e. a refining of the tin block prior to sale, a process which was carried out in a market town. (For further discussion of this point see Section 4.6.3) The new tax imposed by De Wrotham was essentially, therefore, a duplicate payment upon a product at different stages in its manufacture.

The process of collecting the tax on tin is in later times called Coinage, from the French '*coin*', meaning corner, because a corner of each block of tin presented to the Crown officials was chiselled off as part of the assessment of the quality of the metal (Lewis 1908 p151, Brooke 1998 p82, p346). What the exact process was in De Wrotham's time is not known, but the weighing of tin, stamping of ingots and collection of duty appears to have been carried out by Wardens and clerks moving between towns, at dates that may have varied from town to town. Later in the Mediaeval period it was established that coinage was carried out twice a year, around Midsummer and Michaelmas (29th September), and at the beginning of the 14th Century, the towns in which this took place were Chagford, Tavistock, Plympton and Ashburton in Devon, and Liskeard (from 1305), Bodmin, Lostwithiel, Helston and Truro in Cornwall. Bodmin remained a coinage town only until the reign of Elizabeth I (Maclean 1874, Lewis 1908 p44-5).

Worth (1910) suggests that Furnum Regis, or King's Oven (SX675813), near Postbridge in Devon, was originally one such appointed place. The name Furnum Regis is first recorded in 1240, as a landmark along the boundary of Dartmoor Forest (Burnard 1889; Crossing 1889-2), but to what the name referred is not clear, for no smelting site is recognized in that vicinity. The name King's Oven is now attached to a

prehistoric cairn, which for some years was assumed to have been an ancient furnace (Greeves 1981a, 1991).

Following the introduction of the duty on the tin of the second smelting, production declined for around a decade, but thereafter increased again, reaching a peak in 1214 of 1200 thousandweights. Only rarely in the 300 years that followed was that level of production to be matched (Hatcher 1973 p154-9).

Unfortunately, in 1215 the revenues garnered from tin production were farmed again, thus once more difficulties in estimating production arise because of the sparseness of the documentary record (Lewis 1908 p37). However, from the sporadic references that are available, it appears that there was a general decline in output from Devon. In 1243 the amount of tin presented for coinage in Devon amounted to just less than 90,000 lbs (40.9 tonnes) (Hatcher 1973 p154-5): much less than estimates for Devon tin production in the 12th Century (see p77). Worth (1910) states that 1243 was the year in which Devon's tin production was overtaken by Cornwall, which ever after remained the greater producer. However, in 1220, the farm of tin from Devon amounted to only one fifth of the farm of Cornish tin (Hatcher 1973 p154), and while this is not a direct comparison of production in the two counties, the difference is sufficiently large to suggest that Cornish production was of greater importance.

From 1300-1 onwards it becomes possible to extract actual production figures from the Coinage Rolls and other records, and also to distinguish between outputs from the two counties. Hatcher (1970 p30, 1973 p152) notes that the true amount of tin produced is likely to be less than that recorded in the Coinage Rolls, because with the tax to be paid on the tin amounting to 20% of its value there would have been some attempts to avoid

payment. However, the fact that the duty remained static over time likely meant that the level of smuggling did not vary greatly.

The record of coinage for Cornwall is relatively complete, with only brief periods when there was some interference with the collection of duty. The same is not true of Devon: revenues from tin production were farmed for most of the 14th Century (Hatcher 1973 p154).

In general, tin production through the 14th and 15th Centuries was greater than in the previous century, although there is wide fluctuation from year to year, and decade to decade (see Table 1.2). The peaks and troughs in the figures show clearly that output was affected by wars and outbreaks of plague. A particularly steep drop coincides with Black Death raging through southwest England between 1348 and 1349: Cornish production in the years immediately following was about one fifth of pre-plague output (Hatcher 1970 p142), and production may have briefly ceased altogether in Devon around 1355 (Lewis 1908 p40, p156). Another fall in production is associated with the second outbreak of plague in 1361-2. Such outbreaks resulted in labour shortages, not only through the deaths of those who worked in the industry, but because many who had previously had no choice but to take on the hard toil of digging for tin would, in the wake of the plague, have taken advantage of the sudden availability of land to make the change to the less arduous labour of farming (Hatcher 1970 p142).

Similar peaks and troughs in production are seen in the 15th Century, although these cannot be attributed to a single cause. Output was high at the beginning of the century, but suffered another severe downturn mid-way through, before rising again.

In addition to providing production statistics for Devon and Cornwall, the Coinage Rolls available from the late Mediaeval period also have the advantage of showing how production varied between different parts of the two counties.

Table 1.2: Weight of Tin Coined in Devon and Cornwall in the 14th and 15th Centuries (Data from Hatcher 1973 p154-9).

Year	Tin Coined in Cornwall / lbs	Tin Coined in Devon / lbs
1301	560335 lb (254698 kg)	63600 lb (28909 kg)
1317	532640 lb (242109 kg)	No data
1338	1228478 lb (558399 kg)	No data
1361	576821 lb (262191 kg)	No data
1379	832048 lb (378204 kg)	86844 lb (39475 kg)
1400	1465298 lb (666045 kg)	135430 lb (61559 kg)
1423	1135038 lb (515926 kg)	142600 lb (64818 kg)
1440	734601 lb (333910 kg)	110340 lb (50155 kg)
1460	621520 lb (282509 kg)	128734 lb (58515 kg)
1478	808950 lb (367705 kg)	254205 lb (115548 kg)
1495	1017260 lb (462391 kg)	262114 lb (119143 kg)

The tinworking areas of Devon and Cornwall were divided into administrative districts called Stannaries, each centred upon a Coinage town (hence these towns are also referred to as Stannary towns). The Stannaries do not appear to have had formally defined boundaries, but in Cornwall the approximate areas involved are as follows: Foweymore Stannary covered the area between Launceston and Bodmin, i.e. the area now known as Bodmin Moor; Blackmore Stannary was based upon the tin grounds between St Austell, Roche and Luxulyan; Tywarnhaile Stannary was a small area between St Agnes and Cligga on the north coast, and Truro; the united Stannaries of Penwith and Kerrier included the tin grounds to the north of Helston in Kerrier, and between Lelant and Land's End (Maclean 1874). In Devon, Dartmoor is roughly quartered by the four Stannaries of Chagford, Ashburton, Plympton and Tavistock (Greeves 1981b).

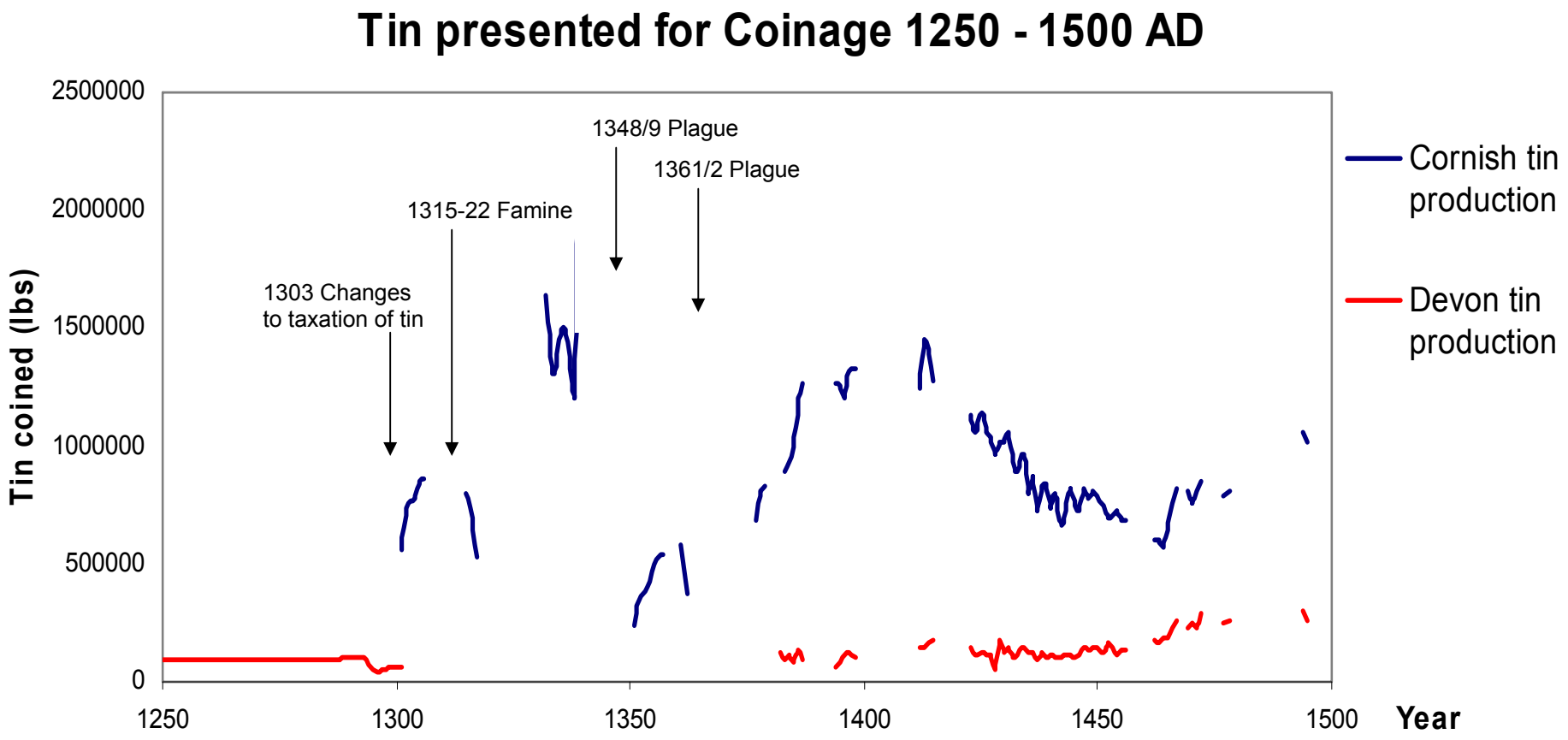


Figure 1.2: Amount of tin metal coined in Devon and Cornwall between 1250 and 1500 (data from Hatcher 1973)

Figures from Devon, starting in 1303, show that the tin coined in Tavistock, in the southwest of Devon, amounted to less than 4% of the total output for the county, however a century later Tavistock accounted for 25% of the total and this continued to increase into the 16th Century (Greeves 1992).

A similar shift is seen in Cornwall. In 1307 Blackmore Stannary, which sent its tin to Lostwithiel to be coined, accounted for over 40% of the total tax assessment. The Stannary of Penwith and Kirrier, which sent tin for coinage at Helston, produced another 40%. The remainder derived from Tywarnaile and Foweymore. Foweymore yielded less than 5% of the total output of Cornish tin in 1307 (Hatcher 1970 p25, p28), and production remained low in comparison to the other areas (Maclean 1874). Over the 14th and 15th Centuries production in eastern Cornwall was overtaken by increases in output from the Stannary of Penwith and Kirrier (Maclean 1874; Lewis 1908 p44-5; Hatcher 1970 p93).

Another important piece of information that can be extracted from the coinage records is the average mass of an ingot or 'piece' of tin. Ingots from Devon were smaller than those produced in Cornwall. In 1305 the average Cornish ingot weighed 126 lbs (57 kg) (Maclean 1874), substantially heavier than ingots known from earlier periods, which rarely exceeded 20kg (see Catalogue of Tin Metal Finds). By the 15th Century Cornish ingots weighed 200-250 lbs (90-114 kg). Ingots from Devon also increased gradually in size through the Mediaeval, ranging from 100-120 lbs (45-55 kg) (Greeves 1981b).

Archaeological finds support the idea of slightly larger ingots for this period, while making it clear that there was no standardization of mass.

Five ingots dredged from the Fowey estuary in 1898, which are believed to have been part of a cargo from a ship that sunk in 1485, had masses of 116, 144, 146, 149, and

167 kg. They were apparently cast in a rough mould, possibly of granite, with gently tapering sides (Penhallurick 1986 p225). The 72 kg St Mawes ingot, now believed Mediaeval on the grounds of its size, has already been mentioned (see p34).

The Stannaries, from at least the early Mediaeval period, had their own laws and privileges (Anon 1753; Worth 1910; Pennington 1973), and ultimately their own parliament. It is not known precisely when the Stannaries were established - they appear to have been extant in some form prior to the appointment of William De Wrotham as Lord Warden, since he was not the first to hold that post - but the main laws under which the tinners conducted their affairs appear to have been set forth by Edmund, Earl of Cornwall, in the latter part of the 13th Century (Lewis 1908 p38; Brooke 1998 p333).

Despite the introduction of feudalism under the Normans, the ancient rights and customs of the tinners were permitted to stand by De Wrotham, permitting them to dig for tin in whatever place they deemed fit, regardless of who owned the land.

These rights 'of digging tin, and turfs for smelting it, at all times, freely and peaceably without hindrance from any man, everywhere in moors and in the fees of bishops, abbots and counts, and of buying faggots to smelt the tin without waste of forest, and of diverting streams for their works, as by ancient usage they have been wont to do' were confirmed in the first Stannary Charter, issued by King John in 1201 (Lewis 1908 p36): '…Et quod possint omni tempore libere et quiete absque alicujus hominis vexatione fodere stannum et turbas ad stannum fundendum ubique in moris et in feodis episcoporum et abbatum et comitum, sicut solebant et consueverunt, et emere buscam ad funturam stanni sine vasto in regardis forestae, et divertere aquas ad operationem eorem in stannariis, sicut de antiqua consuetudine consueverunt'. (A transcript of the

document is given in Lewis (1908 p238, p239-41), and Halsall (1998) provides a translation.)

Hatcher (1973 p20) suggests that the Charter, which granted extensive privileges, was to some extent intended as compensation for the additional 1 mark tax that had been imposed three years earlier by De Wrotham upon the refined tin, although the charter did itself impose additional constraints upon the tinners.

A second Charter (or more strictly a pair of Charters, one to each county) was granted in 1305, by King Edward I, perhaps to breathe new life into the industry at a time when production was at low ebb.

The wording of the Charters is of interest in that it speaks of digging for turf to smelt tin, but also of buying faggots for that purpose. It is therefore clear that two sources of fuel, peat and wood, were used for smelting, and had been used for some time prior to 1201 such that the activity could be described as 'by ancient usage'. Later descriptions of smelting, for example that given by the Anonymous Writer in 1670, state that peat charcoal was the fuel of choice for alluvial tin ore, while a mixture of peat and wood charcoals - the latter burning hotter - was used for vein ore.

Further support for the use of peat charcoal as a fuel for smelting is found in a document of 1219, in which the King commands William Briwere to permit the men of Queen Joan to 'dig, burn and lead away from the turbary of Dartmoor to her Stannary as they used and ought' (Worth 1953 p327), a 'turbary' being an area from which peat turfs are extracted.

Hatcher (1970, p188) details the drop in revenue from the sale of peat turfs between the 14th and 15th Centuries caused by the apparent working out of the turbaries attached to

various manors. The demand for peat charcoal was still high, however, and it was stated, in a document dating to 1466, that Cornish tinners were granted the right to 'dig turves in Dartmoor and take them back to Cornwall to melt their tin with… as the lands, moors, wastes and groves in their own county have been so devastated of turf they cannot get enough to melt their tin and have left unworked many mines.'

1.4.5.2: Methods of Ore Extraction

There is a certain amount of evidence, both physical and documentary, pertaining to ore extraction in the Mediaeval period, and this suggests that the majority of cassiterite being used was initially from alluvial and eluvial deposits, which ties in with the high demand for peat charcoal. Some of the streamworks from which this ore was obtained were quite substantial: Hatcher (1973 p45) states that streamworks might employ up to 50 people, while Austin et al (1989) note that in 1357 Abraham le Tynnere claimed to employ 300 men.

There are very few finds of this period associated with streamworks. In Devon, the handle of a jug, thought to date between 1450-1600, was discovered at Golden Dagger Mine (SX682803) (Greeves 1981b), while coins, including an Edward III penny, have been found in various Cornish streamworks, and there is also a wooden shovel – one of three discovered in streamworks at Boscarne (SX039675) – that is believed to be Mediaeval (Penhallurick 1986 p211).

The documentary record is more forthcoming, although no document gives any real detail regarding the process of extraction. A streamwork at Dry Lake, Devon (c.SX640634), was mentioned in 1240 (Rowe 1848 p165), and the aforementioned Abraham le Tynnere is recorded as owning several tinworks within Foweymore Stannary, four of which were specifically described as 'stremworks' (Gerrard 1987);

while in 1387 there is reference to a legal dispute between a group of streamers and a landowner that lasted 16 years (Hamilton-Jenkin 1961 p7). The names of several tinworks from the Mediaeval period also imply that they were streamworks: Clennacombe Streme and Gallidnowe New Streame bounds being examples (Gerrard 1987). Gerrard draws attention to a complaint made in 1361 by John de Treeures (modern day Trerice) about tinners invading his land, which he believes is consistent with streaming for eluvial ore. However, Gerrard suggests that in general contemporary documentation makes no distinction between alluvial and eluvial streamworks because the tinners themselves did not recognize a difference, the methods of extraction being so similar. Herring (1996) suggests that there may have been seasonal shifts between alluvial streamworks, which were drier and more easily drained in summer, and eluvial deposits, which if worked in winter would have the benefit of an increased water supply. However, Herring also notes that alluvial streamworking, which concentrated on wetter and consequently heavier deposits, would require greater capital investment and labour than eluvial works.

Alluvial cassiterite is often finely disseminated through the sediment. A streamwork containing 3% tin metal by weight would be considered a rich deposit; poorer deposits, down to 0.2% tin metal by weight, are workable (Earl 1994). It was therefore necessary for the tinners to remove the gangue associated with the ore, and this was accomplished by washing: the less dense minerals that comprised the gangue were removed by a flow of water, leaving behind the denser cassiterite and any large pebbles which could easily be removed by hand.

Both the Stannary Charters of 1201 and 1305 mention the right of diverting streams, and many of the earliest references to tin working relate to the problems associated with

the discharge of sediment from tinworks. For instance in 1356, the Duke of Cornwall suspended tinworking in Foweymore as the sheer volume of silt being generated was threatening the harbour of Lostwithiel (Hatcher 1973 p45).

Recent work by Thorndycraft et al (2004) has shown that floodplain aggradation owing to massively increased sediment supply occurred in the Erme Valley of Devon between AD 1288 and 1389, coinciding with the peak in Dartmoor tin production. Similarly, a study by West and co-workers (West et al 1997) on tin concentrations in peat from Crift Down in Cornwall (SX064598) show elevated levels between AD 895 and 1155, which they attribute to the presence of fine-grained ore released during the working of cassiterite deposits in the vicinity.

The Stannary Charters give not even a hint that underground mining took place, and Lewis (1908 p5) argues that streamworks provided all the cassiterite smelted in Cornwall in 1297, but Gerrard (1987) expresses concerns about the reasoning behind this claim, concluding that there is insufficient evidence for such an assertion. It is possible that there was exploitation of vein ores where these outcropped, e.g. at coastal sites. It is also a small step from streaming to lode-back mining – the simplest form of shaft mining, where tinners dig a series of pits to follow the line of a near-surface lode (Gerrard 1996). Gerrard (1997) suggests a late 13th Century date for the commencement of lode mining, on these grounds: firstly, the Coinage figures for 1297 show western tinworks were in operation, but were less productive than tinworks in the east, suggesting that they were mines rather than streams; secondly, in 1296 miners were taken from Cornwall to work the Coombe Martin silver mines; and thirdly, tin mills, which would be required to crush vein ore (although some alluvial ores would also have required crushing), were introduced around this time - the first documented

example being at Penenkos in Cornwall (SW6944), in 1402 (Michell 1978). (Ore processing mills are not recorded in Devon until 1504, when reference is made to one at Ashburton (Amery 1924; Worth 1953 p321)).

A tin mine at Glen (location now unknown) is recorded in the Black Prince's Register in 1357 (Gerrard 1987), and Carew, writing in 1602, states that the adventurers (i.e. streamers and miners) of his day reworked the rubble cast up by tinners from 'old stream and *lode works*' (Carew 1602 p21). Additional circumstantial evidence for mining comes from Godolphin (SW6032), where it is traditionally told that the men who built the tower at 15th Century Germoe Church were responsible for cutting a level in Great Work mine (Herring 1998 p84).

Through time, as streamworks became exhausted, or the alluvial ores became more inaccessible, the proportion of lode ore being smelted would have increased. The shift in production between Blackmore and Foweymore Stannaries in the east, where many rich streamworks were to be found, towards the western Stannaries, has already been mentioned (see p84). The increase in the amount of ore being obtained from Penwith, where alluvial deposits were not abundant, implies that lode working was taking off and that better methods of processing vein ores and/or better methods of smelting those ores had been introduced.

As a prelude to the hydraulic separation of cassiterite and gangue some ores would require crushing. This perhaps explains the presence of stone hammers at the Crift Farm smelting site (SX067602). Herring (2005) notes that primitive hand mortars have been found on Bodmin Moor near Trebartha (SX255776), where streaming remained the dominant extraction technique, and Earl (2002) suggests that hand mortars may have been used in the Penwith area, where vein ores were being exploited.

In the later Mediaeval, it appears two methods of crushing were in use: stamping, which used a heavy beam to pulverize dry ore placed upon a hard surface, and crazing, which utilized circular millstones, similar to those used for grinding corn. Both stamping and crazing mills are recorded as working at Penenkos in 1402. Crazing may be the earlier of the two methods. No examples of early stamps survive, but a broken crazing stone was found at the early Mediaeval Crift Farm site (Buckley and Earl 1990, McDonnell 1993a, 1993b, 1995) (Figure 1.3). This crazing stone would originally have formed a circular slab, 5-6 cm thick and approximately 45 cm across, with a 7 cm diameter central hole. The working surface, worn smooth but for a number of concentric striations, was slightly concave in shape. Crazing stones are discussed further in Section 1.4.6.

Figure 1.3: Crazing stone from Crift Farm

1.4.5.3: Smelting

Unfortunately, the documentary record is silent on the exact process of smelting, and no descriptions of Early Mediaeval furnaces exist. It is generally believed that there was a change from the use of small shaft furnaces where the air supply to the furnace was

provided by hand-powered bellows, to somewhat larger shafts that utilized a waterwheel to harness the power of a stream or river to drive the bellows. Exactly when this change took place is uncertain, though a date around the early 1300s is usually assumed. (The adoption of water mills for industrial purposes in western Europe is believed to have begun in the 13th Century, although corn-mills used the technology much earlier.)

Both archaeological and documentary sources attest that the smelting furnaces of later times used waterpower to provide the furnace draught, and the buildings that housed these furnaces were called 'blowing houses'. (In fact the term mainly applies to Cornish smelting sites; it was not commonly used in Devon until the later 17th Century - in Devon the less specific 'tin mill' was used for a building in which smelting, ore processing or both was carried out (Greeves 1981b)). The introduction of this terminology may be contemporary with the introduction of the technology.

The earliest reference to a blowing house records William Pasford and Thomas Quoynte as joint lessees of the 'Blouynghous and Weghynghous' at Lostwithiel (PRO C143, File 185 No 6), which was the main coinage town at that time. This establishment may have been connected with the coinage process; in 1332 Pasford (on behalf of another) paid duty upon 14 thousandweight (6364 kg) of tin (Hatcher 1970 p239).

Further references occur: in 1337, to a blowing house at Polmarth (Hull 1971 p89-90); in 1359, when it is recorded that the Black Prince shared in the profits of several blowing houses situated in Lostwithiel; in 1426, when one John Aunger of Cornwall is described as a 'husbandman and blower' (Lewis 1908 p17); in 1463, when a Roger Bond was granted a license to construct two mills, one for corn, the other a

'blowyngmille' on Glamaryn water at Calstock manor in eastern Cornwall (Hatcher 1970 p161); in 1435, when David Abbot of Clive conveyed to Sir John Trelawney and his son Richard one half of the mill at Hurdon as a blowing house (RIC HEND Vol 23 p4); and in 1495, when new Stannary ordinances are introduced to cover blowing house marks and swearing in of blowers (Lewis 1908 p17).

The new water-powered technology would have provided a stronger draught than had previously been available using hand powered bellows. This would have allowed larger furnaces to be constructed, but there were also disadvantages to having a more powerful blast, not least that contaminating elements within the tin ore were more liable to be co-smelted. A discussion of the consequences of adopting water-power is given in Section 4.1.2.2.

Archaeological evidence for the Mediaeval blowing house or its predecessor is scant. Vague descriptions of seemingly primitive smelting places, often referred to as Jew's Houses, are not uncommon in the antiquarian journals, and some of these are likely to be Mediaeval, though many an author prior to the 20th Century failed to consider an explanation so mundane. One such Jew's House, associated with fragments of tin metal mixed with charcoal, was discovered some years before 1891 on Shirehall Moor, to the south of Lostwithiel (Hext 1891 p155-6). Unfortunately, the precise area in which the remains were situated is not known.

The idea has developed that, prior to the introduction of the blowing house which used water-powered bellows, furnaces consisted of funnel-shaped cavities built into clay banks, with bellows delivering an air blast to the base through a channel to the side, where the molten tin also discharged (Hamilton-Jenkin 1927 p68; Brooke 1998 p217).

This was based upon the description of the furnace discovered at Trereife, discussed in Section 1.4.3 (p63).

Two sites of Mediaeval date, Brownie Cross (SX546609) and Crift Farm (SX067602), have been identified as possibly having furnaces that were not reliant on water-power for the furnace draught.

The Brownie Cross site (SX546609), discovered during the laying of a pipeline, was excavated in 2009 and tentatively identified as a blowing house (Taylor 2009, 2010). It consisted of the insubstantial remains of a pair of buildings, which were associated with pottery provisionally dated to the 13th/14th Centuries. It was situated on high ground where there was no obvious source of water suitable for powering a bellows, and a pit inside the structure, which may have contained the furnace, was located too close to the walls to have accommodated a bellows. Within the building was a granite mouldstone, while outside was a large spread of slag. Charcoal fragments were also recovered from the site.

The only other site from the period in question that possesses any evidence for tin smelting is Crift Farm (SX067602), which lies close to the rich alluvial tin grounds of Red Moor (c.SX0661). (In view of the proximity of Crift Farm to the village of Lanlivery (SX079590), it is interesting that Henwood (1873/4) remarks upon the discovery around the year 1855 of a Jew's House at Lanlivery, complete with specimens of ore and metallic tin. Unfortunately, it is impossible to say whether this Jew's House and the Crift Farm site are one and the same.)

Over a period of years, surface finds relating to metallurgical processes had been discovered at the Crift Farm site, including a large smithing hearth-bottom formed of solidified iron slag, and stone hammers that were similar in appearance to prehistoric

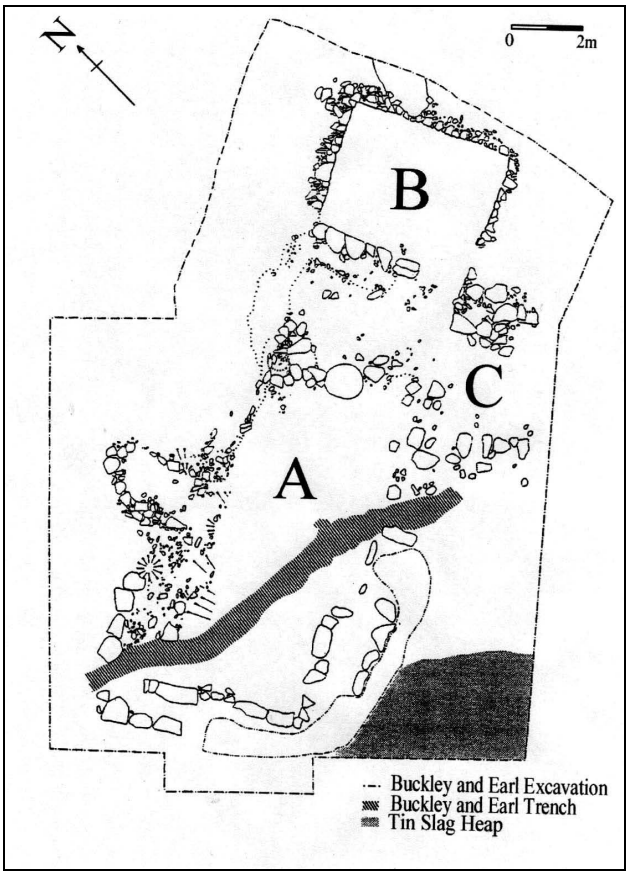
tools (Figure 1.4). Tin slag was first discovered in 1975, during deep ploughing, which eventually led to a small-scale excavation being carried out in 1989 (Higgs and Earl 1989; Buckley and Earl 1990). A stone structure associated with the slag spread was uncovered, but owing to the limited extent of the excavation this was initially interpreted as a hut circle (the westernmost of the group of roundhouses which can be seen in adjacent fields). Within the tumble of the building's cob walls were shaped stones of fine-grained granite identifiable as hammer stones, and two pieces of a crazing stone made of the local coarse-grained granite. Excavation through what was believed to be the centre of the hut circle revealed a quantity of tin slag, slagged granite, coarse pottery and a pit lined with stones and luted with a mixture of sand, clay, granite fragments and charcoal, and since it contained a layer of iron hammerscale, the structure was interpreted as a quenching trough or 'bosh' associated with iron working. A small iron smithing hearth-bottom was also found in the vicinity of the bosh pit, and a sample of charcoal separated from it was later radiocarbon dated to AD 1145 (880 BP ± 60; calibrated to AD 1040-1225 1σ and AD 1020-1270 2σ (Hedges et al 1992)).

Figure 1.4: Stone ore crushing tools from Crift Farm

Elsewhere in the building was a three-sided arrangement of granite blocks, which Buckley and Earl identified as a possible furnace hearth, although subsequent investigations suggested that it was part of the building's structure. Large quantities of tin slag were also located, in what appeared to be a dump outside the building.

Further excavations were carried out by the University of Bradford between 1992 and 1995 (McDonnell 1993a, 1993b, 1995), exposing not a roundhouse but a sub-rectangular structure (see Figure 1.5), with apparently more than one phase of building. The earliest part, Building A, resembled a Cornish longhouse and consisted of large blocks of the local granite placed in two parallel rows - the remains of cob-walling.

Figure 1.5: Plan of the Crift Farm Excavation (from McDonnell 1995).



Against the eastern-most short wall of this building, a second smaller building (B) had been constructed, using small granite blocks for the three new walls. A third small

building (C) was added to the original building against the southernmost long wall (see Figures 1.6 and 1.7).

Figure 1.6: The Crift Farm smelting site. The remains of Building B are in the centre, and Building C in the foreground, left.

Figure 1.7: The Crift Farm smelting site. The remains of Building A are in the foreground, left. The slag heap is the de-turfed raised area on the right.

Outside the earliest building lay the slagheap that had been partially revealed by Buckley and Earl. Work in this area showed that the dump contained an estimated

tonne of tin slag (the greatest quantity from any archaeological site known at that time), but that it developed over a period of time, with small discrete deposits of slag being placed on the heap. Chemical analysis of the Crift Farm slag has been carried out by several workers (Tylecote et al 1989; Adriaens 1996; Aylett 1996 p38-45; Malham 1996 p56-8, 2002, 2003). Data from additional samples is presented in Section 3.1.

Unfortunately, owing to the poor preservation of Building A and the fact that the earlier excavations had removed much of the material between the building and the slagheap, the exact relationship between the two could not be established. However, given that broken stone tools and slag were incorporated into the fabric of Building A, it was considered that tin working could predate its construction, or be contemporary if material was emplaced during renovation.

Geophysical survey of the area around the excavation site failed to reveal additional structures or settlement activity in the field.

In addition to slag, small pieces of slagged granite were found in the slagheap, and these have been interpreted as pieces of furnace lining. A single angular fragment of tin ore and a ceramic tube, possibly a nozzle for a bellows (though that identification remains uncertain), were also found, both in unstratified contexts.

From the artefacts recovered from the Crift Farm site, it seems clear that iron and tin working were being carried out, though the exact relationship between the tin and iron slags has not been resolved, and the two may not be contemporary, which is a problem as the radiocarbon date obtained relates to the iron working and not to the tin working.

The presence of poor quality Lostwithiel Ware pottery in contexts associated with metalworking gave support to the radiocarbon date, and on this evidence a date

between the 10th and 14th Centuries AD has been postulated, but the ceramics do not permit an accurate dating sequence for the site to be established.

The site is notably absent from the Lanhydrock Atlas, a detailed record compiled in 1695 of the lands of the Robert's family, whose wealth was founded upon the tin industry. The field in which the site is located shows no structures, though a windmill and several roundhouses are shown in adjacent fields, suggesting that the longhouse had decayed to the point where it did not warrant inclusion. The site must therefore substantially predate the map.

With regard to tin, questions remain regarding what processes were carried out on the site. Buckley and Earl (1990) state that there is evidence for reprocessing of the tin-rich slags, though they do not rule out primary smelting of ores. The possibility that slag was brought in from elsewhere for use as hardcore must also be considered. These issues will be discussed further in Section 4.6.1.

If smelting did indeed take place at the Crift Farm site, its location near the top of Crift Down, c.180 m above sea level, precludes any use of waterpower to operate bellows, since it is well above the spring line. No natural streams flow on the heights, nor have any artificial watercourses been discovered.

Remains believed to be an early blowing house were found at Goldherring (SW411282) during excavations of the Romano-British settlement there in 1958-61 (Guthrie 1969). One rectangular building (Site B in Guthrie's excavation report) appeared to have been repaired, and within it was a feature described as a sub-oval hearth, paved at the base and walled with irregular shaped granite blocks. A covered air duct led out from the hearth. Both the hearth and the air duct were filled with several centimetres of gorse charcoal, and sealed within the charcoal layer in the duct was a piece of 13th Century

pottery. A small broken mortar, which could have been used for ore processing, was discovered within the building.

Within the settlement as a whole three pebbles of cassiterite were found, but the mortar and pebbles may not be contemporary.

There is no mention of slag being discovered anywhere at the site, which strongly suggests that smelting was not carried out there, and Guthrie reports that no residual tin was found within the charcoal. However, the writer who reported on Penzance Natural History and Antiquarian Society's visit to view the Jew's Smelting House in 1885, appears to suggest that a 'lump of smelted metal' found a short time earlier came from the Site B building (Anon 1885-6). Unfortunately, the find was neither weighed nor measured, and is now lost. It is possible that this was a solidified dribble of tin that had escaped the furnace, but it may have been metal used in alloying.

The date of the site and its location on the heights some considerable distance from a water source suitable for driving bellows makes the identification of the building as a blowing house unlikely. Moreover, there is no real evidence that the structure was used for smelting rather than secondary metal-working.

The status of a site located at Hurdon in Cornwall (SX210823) is in no doubt, as documentary sources attest to its use (see p93). Today all that remains is a low rectangular earthwork measuring 7m by 4m, which is situated downslope from a leat that served a 19th Century grist mill (Gerrard 1986 p279). This is one of the few blowing houses from Cornwall for which archaeological evidence has been traced, and may be the earliest that survives today in any form. Twenty fragments of slag were found by Gerrard in molehills close to the earthwork, and several more were found by the present author in cow trample beside the nearby farm track. Analysis of the slag has

been carried out, and is presented in Malham (1996 p127-8). Further analysis will be given in Section 3.1.

1.4.6: The Post-mediaeval Period (AD 1500 to AD 1700)

1.4.6.1: Production from the 16th Century

From AD 1500 onward, the documentary evidence relating to tin smelting becomes richer. Although during the Commonwealth period the amounts of tin produced in Devon and Cornwall were combined, so individual figures are lacking for the years 1645 to 1676, more often than not Coinage Rolls continue to show different levels of production in Devon and Cornwall (Lewis 1908 p259-64; Hatcher 1973 p155-9), and allow quantities of tin obtained from different areas of the two counties to be tracked through the amount of tin brought to each Coinage town. There were some changes to the Coinage towns in the Post-Mediaeval period: Bodmin lost its status in the reign of Elizabeth I, while Penzance was added to the list of designated towns in 1663 (Lewis 1908 p44-5): a response to the decreasing amounts of tin being obtained from Bodmin Moor and the shift in production to central areas of Cornwall, and increasingly to the Land's End district.

The overall picture at the beginning of the 16th Century is one of a small but thriving industry in Devon; production reached a peak in 1524, but from 1550 a steady decline is seen (Worth 1910; Hatcher 1973 p159) (see Table 1.3 and Figure 1.8). The Civil War brought Devon's tin industry almost to a standstill, and though production resumed afterwards, it remained relatively modest in comparison with before. Of the Dartmoor Stannaries, Tavistock gained increasing importance, at times during the 17th Century accounting for as much as 80% of Devon's tin production (Greeves 1992; Greeves & Newman 1994).

Cornish output far exceeded that of Devon, and though there were slumps and peaks, the general trend in production was upward. Output from the eastern Stannaries, coined

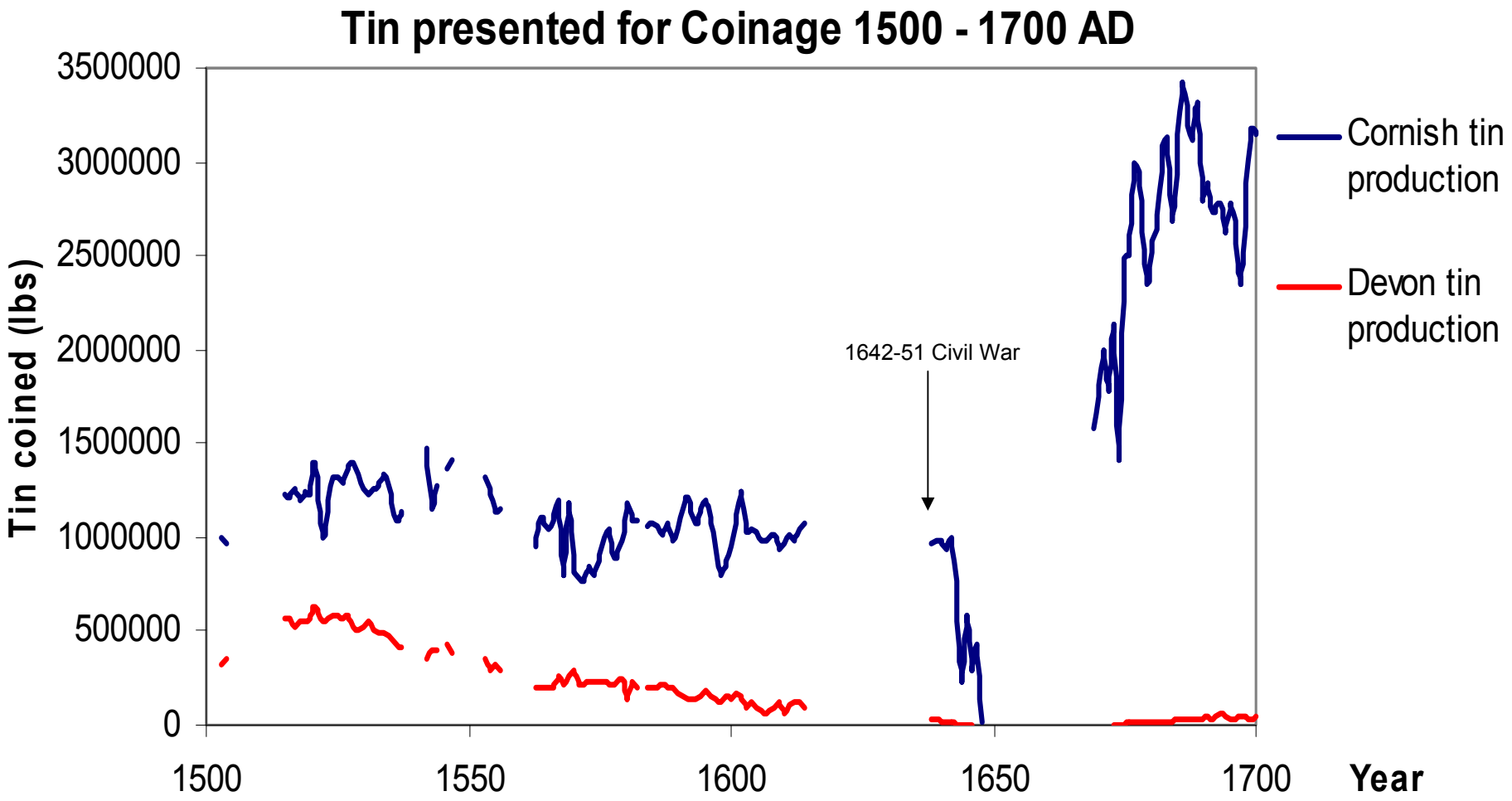


Figure 1.8: Amount of tin metal coined in Devon and Cornwall between 1500 and 1700 (data from Hatcher 1973 and Lewis 1908)

at Lostwithiel and Liskeard, nonetheless showed a decline: figures presented by Maclean (1874) illustrate a roughly 50% fall in production between 1577 and 1607. Meanwhile the records for Truro and Helston show that the western Stannaries, each already producing around three times as much tin as was coined in Lostwithiel in 1577, experienced further growth during the period in question.

Table 1.3: Tin Coined in Devon and Cornwall in the 16th and 17th Centuries
(Data from * Hatcher 1973 p154-9 and ^ Lewis 1908 p252-8).
Note: Figures are given in pounds for years 1503-1539 and 1673-1700. Figures for the years 1561-1640 are given in Stannary thousandweights (M) of 1000 lbs for Cornwall and 1200 lbs for Devon.

Year	Tin Coined in Cornwall	Tin Coined in Devon
1503*	997316 lb (453326 kg)	327541 lb (148882 kg)
1520*	1222076 lb (555489 kg)	571465 lb (259757 kg)
1539*	1377282 lb (626037 kg)	374580 lb (170264 kg)
1561^	1162 M (528182 kg)	171 M (93273 kg)
1580^	1182 M (537273 kg)	188 M (102546 kg)
1600^	946 M (430000 kg)	119 M (64909 kg)
1625^	1334 M (610909 kg)	68 M (37091 kg)
1640^	983 M (446818 kg)	18 M (9818 kg)
1673^	2141064 lb (973211 kg)	640 lb (291 kg)
1680^	2586212 lb (1175551 kg)	14930 lb (6786 kg)
1700^	3151504 lb (1432502 kg)	47384 lb (21538 kg)

In addition to fiscal records, documents exist detailing the legal and administrative workings of the Stannaries, from which clues can be drawn regarding the operation of blowing houses. There are also documents relating to the leasing, sale or inheritance of blowing houses, which have been of use in locating and dating the remains of surviving buildings.

The earliest reference to a particular site in Devon is in 1502, when false metal was smelted ‘at Oldmede within the parish of Chittestor’, probably Yellowmead blowing

house (SX57426755). A mill for blowing and stamping was built shortly before 1514 at Dartmeet (Greeves 1981b), while at Blackaton (c.SX700779) ‘an old house sumtyme a Blowynge house’ is recorded in 1566 (French & Linehan 1963).

Unfortunately, the vast majority of the documentary evidence, which is heavily weighted towards the tin industry in Cornwall, relates to blowing houses of which no trace now exists, possibly owing to the proximity of Cornish blowing houses to centres of habitation, which led to their being dismantled for building materials, or adapted for alternative uses. Examples of blowing houses being reused include Scaweswater, near Idless (SW8247) (RIC HEND Vol 1), Treworder (SW7846) (RIC HEND Vol 9 p102), and Penryn (SW775350) (CRO Coode-French Records), which were converted to grist mills; Polmooth (SW808458) became a paper mill (RIC Boscawen State of Rent Accounts 1782); mills in Lanivet (SX0365) and Kennall Vale (SW7537) became dwellings (RIC Arundell Manor Survey) (Barton 1971, p69-72).

Several researchers have compiled lists of blowing houses. Barton (1971 p59, p62-82) detailed the Post-Mediaeval and later blowing houses of Cornwall, stating that around 60 were known from written sources, though few of these can be identified in the archaeological record. Gerrard (1986 p160) provided a summary of 96 Cornish sites, mainly dating to before AD 1700; 15 of these are 16th Century. Greeves (1991) lists the tin mills of Dartmoor, which largely date to the Post-Mediaeval. Out of more than 100 tin mills known to have existed, just over 60 have surviving remains, the remainder being known solely through documentary references. Only around a quarter of Devon mills can be positively identified as blowing houses, the majority being used only for stamping. (A summary of known blowing houses is provided in the Catalogue of Smelting Sites.)

The true number of blowing houses that existed may be higher than these figures suggest. Gerrard (2000 p132) estimated that to account for the tin coined in a typical year in the Post-medieval period there must have been around 120 blowing houses in operation. A similar calculation carried out by Greeves, for Devon, gave a requirement of 48 (Greeves 1981a). These calculations are based upon observations of the tin industry by the Cornish gentleman Richard Carew whose Survey of Cornwall was published in 1602. Carew noted that blowing houses worked for only two or three months of the year, in the run up to the coinages held at midsummer and Michaelmas (29th September). Greeves has suggested that there may have been smelting on perhaps as few as 40 days. However, some houses were probably more popular than others, and so worked longer. The accounts of Lenobray house (SW6947), for example, show that it worked for at least 78 days in 1692 (Gerrard 1986 p157).

1.4.6.2: Methods of Ore Extraction

Evidence for ore extraction points to the continued use of alluvial cassiterite, but increasingly mined ores were being used.

In his account of the Stannary of Blackmore (i.e. the Hensbarrow area, north of St Austell), Beare (1586 p72-6, p95-7) mentions tin streaming, and implies that there were several different types of streamwork, but he makes no mention of underground mining, suggesting that Blackmore Stannary was still for the most part reliant on its alluvial and eluvial tin deposits. However, in his description of the blowing process (p106) he does state that he has obtained some tin ore 'being some streamwork tin and some mine tin'.

Carew (1602 p19) and an anonymous 17th Century writer (Anon 1670) both distinguish between 'moor works' and 'stream works', possibly making a distinction between eluvial and alluvial cassiterite respectively (Gerrard 1987).

That exploitation of the parent lodes also took place is clear from accounts by Leland in the 1530s (Hearne 1769), Camden c.1540 (Webster 1671 p289) and Norden in 1584 (p12). Camden mentions both 'loadworks' and 'streamworks', and Norden's account of prospecting states, 'both the stream and lode-works are found by little stones, which lie both in, and near, the brooks, and upon the mountains, where the metal lieth: and these stones they call the shoade, being parcel of the vein of ore, which being dismembered from the body of the lode, are means to direct to the place of profit…'.

Carew (1602 p19) also refers to 'two types of tin works, stream and lode', and goes on to explain how the distribution of shoad was used to locate 'load works'. In 1670 the anonymous writer provided a more detailed description of this process (Anon 1670).

Discussions of the documentary evidence relating to the different methods of tin working in the Post-Mediaeval, and reports of surveys of surviving archaeological remains, are provided by several authors including Gerrard (1987, 1997 p83-91, 2000 p26-31), Greeves (1981a), Sharpe (1993 p23) and Herring (1996). The consensus is that alluvial deposits continued to be exploited wherever possible, but that there was increasing reliance upon lode ores. Hatcher (1973 p46) suggests the reluctance to abandon alluvial working was a matter of cost rather than lack of technical expertise. The creation of an underground mine, requiring drainage and ventilation, would be an expensive undertaking compared to an alluvial work. As vein ore generally contains more impurities than alluvial material, this may also have been a factor: Carew (1602

p29) refers to ‘good moor-tin (which is counted the best sort)’ and ‘mine tin (which is meaner)’.

It is apparent that there was not the same requirement to switch from alluvial to vein ore everywhere in the southwest. That streaming continued be a favoured method of ore extraction in the 16th Century in the east of Cornwall, and also continued in Devon, is supported by the documentary record: in 1532, the harbours of Falmouth, Fowey and Plymouth were threatened by silt from streamworks to such an extent that it was necessary – as in 1356 – for measures be taken to limit the damage (Hatcher 1973 p45). Problems were also recorded in Devon in 1576 (Burnard 1888).

Sediments studied by Thorndycraft and co-workers show evidence for streaming activity in the Avon Valley of Devon around AD 1448-1621 (Thorndycraft et al 2004).

Archaeological surveying on Bodmin Moor has shown that there was intense exploitation of alluvial deposits, including reworking of the spoils of earlier tinworks (Sharpe 1993 p23). Carew (1602 p21) describes reworking of ‘such old stream and lode works as by the former adventurers have been given over’. Streamworks became increasingly extensive, reaching depths of tens of metres.

Yet even on Bodmin Moor, where the alluvium was particularly rich, lode working occurred; e.g. shallow underground mining by 1570 at Clanacombe Beamwork, where an underlying lode was exposed by streaming (Sharpe 1993 p23). Exploitation of lodes was mostly by opencast working, and elsewhere it was more prevalent than on Bodmin Moor. Openworks, which could be over 50 feet deep (15m), were usually termed coffins or goffens in Cornwall (Hamilton-Jenkin 1927 p43), but in Devon were known as beams or bemes (Greeves 1981b).

The increasing quantities of tin coined in the Stannaries of central Cornwall came as a direct result of the adoption of opencast working in these areas. There were 'no greater Tynne workes yn al Cornwal than be on Sir Wylliam Godolcan's Ground', according to Leland, who visited the Godolphin estate (SW6032) in the 1530s (Hearne 1769), and Herring's survey of the mining remains suggests that openworks and lode back mining were in use there in the 16th Century (Herring 1998 p84-5).

No similar boom in production appears to have occurred in the Land's End district; the deep mines that in the 18th Century would delve beneath the coastal cliffs were still relatively minor near-surface workings. Barton (1971 p62) notes only one blowing house serving the district in 1660, and Penzance was not made a Coinage town until three years later.

On Dartmoor the remains of over 300 openworks have been recognized (Gerrard 1997 p78), concentrated in the southwest. The earliest record of a Devon beamwork is Joysbeme, in 1511. Greeves has found references to over 150 more (Greeves 1981b), and notes that the lack of evidence for opencast mining after the 17th Century suggests the openworks are earlier.

Eventually, the greatest of the openworks would develop into true underground mines as the tinners pursued the lode to ever greater depth, such as at Godolphin where they became Godolphin Bal (mines in Cornwall, and occasionally Devon, are commonly referred to as Bals or Balls) and Great Work Mine.

The earliest reference to a shaft in Cornwall is in 1536: John Haymor of Roslyn (modern Roselidden) (SW673295) was ordered to fill in the shafts after raising tin without permission (Brooke 1998 p140).

Some 16th Century Cornish mines appear to have reached considerable depth: Carew (1602 p23) indicates shafts of '40 or 50 fathoms' (73-91 m), while Kalmeter stated that a mine at Trevascus (Trevaskis) (SW607384), commonly held to be one of the oldest on Cornwall, reached a depth of 24 fathoms (44m) (Brooke 1998 p129).

Documentary evidence for underground working in Devon is less certain. Greeves has summarised what evidence there is for it. The earliest possible reference derives from court proceedings in 1521, which includes a statement from one Walter Langsford to the effect that he and his partners had 'goottyn above gronde blacke Tyne to the valewe of a c li' (£100) from a tinwork called 'Fursse Hill' or otherwise 'Fursseball' that had been in operation 'long before' (Greeves 1981b; Greeves and Newman 1994). It is uncertain whether this refers to a shaft mine or openwork, but it does suggest lode ore was obtained by some means, and there are reports that in the 1860s old workings were discovered, almost 100m below ground, at Furzehill Mine (SX517692) (Hamilton-Jenkin 1974 p125; Greeves 1981b).

Supporting an early date for underground working is a description of probable deep mining by Hooker, written in the 1590s: 'His life most commonly is in pits and caves under the ground of a great depth and in great danger because the earth above his head is in sundry places crossed and posted over with timber' (Blake 1915).

Though unequivocal references to shaft mining are absent from the records of Devon until very late - shafts are not mentioned specifically until 1715, when there is reference to one at Bottle Hill Mine (SX564587) (Hamilton-Jenkin 1974 p125-6; Greeves 1981b) - mention of underground works in the form of adits certainly do occur. Adits appear to have been cut as a means of prospecting for tin bearing lodes, as well as providing drainage for existing works. Gerrard (2000 p29) notes that in 1617, one Nicholas Harris

was granted ‘liberty to drive and work the adit now being driven home on the loade’, while in 1659 another adit, which would have cut for a distance of 2 miles through Kit Hill (SX3771), was proposed (though never constructed). There is also reference in 1689 to an adit, somewhere near Ashburton, said to be old at that time (Greeves 1981b).

Gerrard (1997 p88), however, is of the opinion that most true mines, i.e. shaft works, on Dartmoor post date AD 1750, and Greeves (1981b) suggests that any early shaft mining would have been concentrated in the more populous and easily accessible areas around the periphery of Dartmoor.

1.4.6.3: Ore Processing

Further clues to when and where lode ores were being exploited may come from the distribution of ore processing mills. Gerrard (1986 p160, 1997 p91) noted that in comparison to blowing mills, the remains of which are fairly evenly distributed across Dartmoor, stamping mills appear to be concentrated in the southwestern part of the moor, which is where lode-back pits and openworks are most common. He went on to observe that on Foweymore, where alluvial deposits continued to be an important source of cassiterite, there were more than twice as many blowing houses as stamping mills because most alluvial ore requires little or no stamping. The central region of Cornwall between Helston and St Agnes possesses the largest proportion of known stamping mills (Gerrard 2000 p108), not only because the amount of tin raised was proportionally greater, but because it derived from lodes.

Although stamping mills were relatively common in Cornwall, with c.150 from pre-1700 known from the documentary record, (Gerrard 1996 p79), subsequent activity has obliterated all sign of the majority; only three survive, plus some stray mortar stones.

By contrast, in Devon, where later mining was minimal, evidence survives for at least 60 stamping mills. Seventy-two have been identified from documentary sources (in which they are variously known as stamping, knocking, knacking, or clash mills (Greeves 1981b)), including the earliest reference to a 'knacking mill' in Devon, operating in Ashburton in 1504 (Amery 1924). Most tin mills date from the 17th Century.

Descriptions of stamps and their method of operation are contained in several 16th and 17th Century accounts, including Carew (1602 p24), who states, '…the tin... is first broken into pieces with hammers, and then carried… to a stamping mill, where three, and in some places six, great logs of timber, bound at the ends with iron, are lifted up by a wheel driven with the water, do break it smaller'. Similarly, the anonymous Inquisitive Person (1670) wrote: 'The Ore slides down into the coffer… wherein [are] the 3 usual Lifters, which serves to break the Ore in the said Coffer…. into small sand, which is washed out by the Cock-water through a brass grate'. The grate was a perforated metal plate, designed to allow through only ore of the requisite size, which was subsequently carried to the settling pits for further washing and dressing (Cotton 1664).

It can be inferred that these later stamps utilized a flow of water to carry the black tin under the stamp heads, and thence to the processing pits known as buddles, without having to halt the machinery. Originally stamps worked dry, a batch of ore being fed beneath the heads and needing to be removed manually once it was crushed. Exactly when wet stamping came into use is not certain, but from Carew's remark (1602 p24) 'Howbeit, of late times they mostly use wet stampers', a 16th Century date can be postulated. There are earlier references to tin mills requiring access to water, but dry

stamps would still have required a waterwheel to raise the lifters. Agricola (p313), in his 1556 account of tin working in Germany, depicts wet stamping, so the technology was certainly in use on the continent around the mid-16th Century.

Dry stamps did not grind the ore sufficiently finely, so black tin subsequently required further crushing in a crazing mill. The introduction of wet stamping did not bring about the immediate demise of the crazing mill, however. Though Carew (1602 p24) observed that wet stamps were most commonly used, he went on to say that there was 'no need of the crazing mills for their best stuff, but only for the crust of their tails'. Following hydraulic separation in the buddle pits, black tin would be divided into the heads (or foreheads), the middle and the tails, the latter consisting of very small particles of cassiterite mixed with gangue. The Inquisitive Person (1670) reports that the tails were re-treated and the tails of this subsequent round of processing (what Carew referred to as the crust) were ground in a crazing mill. Dr Cotton (1664) makes a similar mention of the crazing mill.

This method of crushing had all but fallen out of use by c.1733, according to Tonkin (Greeves 1981b quoting Carew 1811 edition), however anecdotal evidence suggests crazing stones remained in use into the 20th Century (C. Wills pers comm.), used, for example, by the independent smelter who worked around Wheal Breage, Godolphin (SW5930), until the 1930s (S. Polglase pers comm.).

Surviving crazing stones are rare. In Cornwall examples are known from Retallack (SW73182979) (where 2 complete stones and 35 fragments were found) (Bryant 1882; Gerrard 1985), Loe Pool Valley (c.SW6524), Bluehills near St Agnes (SW725516) (Gerrard 2000 p121), and Godolphin (SW603320) (Earl 1991 p49; Gerrard 2000 p121). Two top stones were also found at the Calenick Smelting works (SW820440), and are

believed to have come from a tin mill that had been on the site previously (Tylecote 1980a). In Devon there are crazing stones at Gobbett (SX64537280) (Amery 1870; Burnard 1888; Worth 1953 p319) and Little Horrabridge (SX51496962) (discovered in a barn along with a mould and many mortar stones, and now part of a flower bed) (Gerrard 2000 p121). Stones reported at Outcombe (SX58016860) (Worth 1933, 1953 p319; Greeves 1981b) and Yellowmead (SX57426755) (Worth 1914, 1953 p319; Greeves 1981b) are no longer visible. The stones are all similar in appearance and size to those found at Crift Farm (SX066603) (see p91).

The lack of crazing stones in the archaeological record may result from the failure to recognize them for what they are, given that they resemble grinding stones from corn mills, but documentary evidence for crazing mills is also scarce, only 13 mills being recorded (Gerrard 1996), all of them in Cornwall (Greeves 1981b). However, Gerrard (1996) suggests that because dry stamping and crazing were merely different parts of the same process, mills were referred to only as stamping mills, while in later periods, when the documentary record is more complete, there were fewer left to be recorded.

Archaeological evidence for stamping is more abundant than for crazing. The presence of mortar stones (see Figure 1.9), which contain oval depressions set (most usually) in pairs or threes, at a mill clearly signifies that stamping was carried out there. (The term ‘mortar stone’ is universally used though the hollows were worn into the block gradually by the stamps pounding upon them, not placed there deliberately.) The archaeological evidence seems clear enough for the Devon mills, but there are very few mortar stones known from Cornwall where production was higher, which has led Gerrard (1985) to suggest a piece of iron or a bed of crushed stone may have been employed, although there is at present no evidence to support or refute the idea. Despite

the detail given in some contemporary descriptions of stamping machinery, not one writer offers any hint as to what lay beneath the stamp heads (Greeves 1981b).

Figure 1.9: Mortar Stone from Week Ford Tin Mill.

As Worth (1953 p321) notes, there is no real need for stamps to be situated inside a building - Borlase (1758 Plate 19) shows open-air stamps with a wooden wheel and mounting – and in such cases only the leat and the worn mortar stones would survive to identify the site. Many stamps were, however, erected within stone structures, and on Dartmoor are the remains of several dozen rectangular buildings with an exterior wheel pit fed by a leat. These mills have been surveyed in some detail (Burnard 1888, 1889; Woodhouse 1901; Crossing 1909; Worth 1889, 1892, 1925-6, 1927, 1929, 1931, 1932, 1933, 1938, 1940, 1946, 1953; French and Linehan 1963; Greeves 1971, 1981a; Newman 1987, 1988, 1990, 1991, 1993, 1998; Earl 1989; Greeves and Newman 1994). A few Cornish stamping mills are known (Gerrard 1989), e.g. Wheal Prosper near

Lanivet (SX573793) (Gerrard and Sharpe 1985), Colliford near St Neot (SX177713) (Austin et al 1989), and Retallack (SW73182979), where at least two survive in the same location (Gerrard 1985).

A few Dartmoor tin mills appear to have had a built-in fireplace, e.g. Black Tor Falls right bank (SX57487162) and Week Ford (SX663723). Carew (1602 p24) states that after crushing 'if the stones be over moist they are dried by the fire in an iron cradle or grate'. What he observed may in fact have been roasting of the ore to burn away impurities that otherwise would have affected the quality of the tin. Though contamination was by no means ubiquitous, lode ores frequently contained sulphide minerals, particularly pyrite (FeS), called mundick by the tinners, and arsenopyrite (FeAsS), known as silver mundick or mispickel. The term mispickel is also used for other arsenical minerals (Earl 1983). Arsenic had a deleterious effect upon the tin, and later refining could not remove it. Hydraulic separation of arsenic minerals and cassiterite during dressing was ineffective owing to their having similar densities, thus the arsenic had to be driven off as vapour before smelting took place. Smith (1996) briefly discusses the chemistry of roasting.

During the 17th Century, as increasing volumes of arsenical ores were mined, purpose-built calcining kilns came into use to treat them. The first mention of such is in 1670. The anonymous writer stated 'when we perceive much Mundick in our Tin (which spoils it by making it britly hard, and not malleable) which we easily discern before knacking (some Loads being much pestered with it, othersome not at all) we are necessitated too burn away this Weed in this Kiln…' (Anon 1670). These calcining kilns resembled the reverberatory furnaces that were used for copper smelting (but not at that time for tin smelting): low-roofed buildings designed to allow the heat of a fire

to be reflected down onto the ore which was spread thinly over a stone shelf. Earl (1985) provides an overview of the calcining process.

The removal of tungsten, titanium and iron minerals, which could neither be hydraulically separated out from the cassiterite, nor volatized, was more problematic.

Dressing using a flow of water was, however, very effective for removing lighter gangue minerals. By the 17th Century it had become quite sophisticated. Following pulverization by wet stamping, the black tin could be subjected to several different treatments depending upon the amount of impurity present (Carew 1602 p24-5; Anon 1670). This permitted even the very fine particles of cassiterite to be separated out, if such was deemed worthwhile.

1.4.6.4: Smelting

Following dressing, the clean black tin was ready to be smelted. This was done in a blowing house, sited where a source of water to power a waterwheel was available. It was also helpful to be convenient to a coinage town or close to the source of ore. These requirements meant that blowing mills, unlike stamping mills, were not concentrated around lode workings, but had a more even distribution throughout (and indeed even beyond) the tin bearing areas (Herring 2005); for example, the only blowing houses in the far west of Cornwall were situated around Penzance, so all black tin from the Penwith district had to be transported there for smelting, and though there are no tin deposits in the immediate vicinity of the coinage town of Truro, there were five blowing houses in the surrounding area (Gerrard 1986 p162).

Occasionally stamping mills and blowing houses were sited together, as with the paired buildings at Week Ford (SX663723) (Newman 1993) and Upper Merrivale

(SX55187665) (Gerrard and Greeves 1991, 1992a, 1992b; Greeves 1994, 1995; Greeves and Passmore 1996), and the complex at Retallack (SW73182979) (Gerrard 1985). Around 20 stand-alone blowing houses on Dartmoor also possess mortar stones (Greeves 1981a, 1991). These may have been used for crushing slag before reprocessing rather than treating ores (Gerrard 1997 p115), but equally the stamps may have served more than one purpose; unless dressing residues are found, as they have been at the Gobbett (SX64537280) and Thornworthy (SX67238443) blowing houses (Worth 1953 p318), it is not possible to distinguish between ore processing and slag crushing.

Blowing houses were more numerous in Cornwall, but most of the surviving archaeological remains are on Dartmoor, probably because, being further from population centres, the Dartmoor buildings were less likely to be destroyed by later mining or agricultural activity, or robbed for stone. Information regarding the archaeological remains of blowing houses from this period can be found in works by, among others, Burnard (1888, 1889), Crossing (1909), Worth (1889, 1892, 1925, 1927, 1929, 1931, 1932, 1933, 1938, 1940, 1946, 1953 p292-314), French and Linehan (1963), Harris (1968 p183-227), Greeves (1971, 1981a, 1981b, 1985, 1991, 1993a, 1993b, 1994, 1994 with Newman, 1995, 1996 with Passmore), Gerrard (1985, 1986 p279-82), Earl (1989), Sharpe (in Herring 2005) and Newman (1993, 1998). Most sites consist only of the shells of the buildings; it is rare that any internal structure survives within a blowing house. It is thus fortunate that there are some contemporary descriptions of the blowing process and of tin smelting furnaces, details of which are summarized in Table 1.4.

The earliest is a manuscript dating to 1586 by Beare, who, not being a tin blower, admitted that his understanding of what he reported was incomplete; in addition he used terms the blowers must have used in connection with their work, so his account is not always totally clear. However, this work has been considered by several researchers, including Greeves (1981a), Earl (1985, 1991), Gerrard (1986 p145-8) and Smith (1996), and it is generally agreed that Beare is describing a furnace (referred to as 'the hearth') served by a single bellows, which entered the furnace through an opening, called the hearth eye, in the back wall of the furnace (see Figure 1.10). Furnaces measuring in the range 0.25 to 0.6m, front to back internally, are suggested.

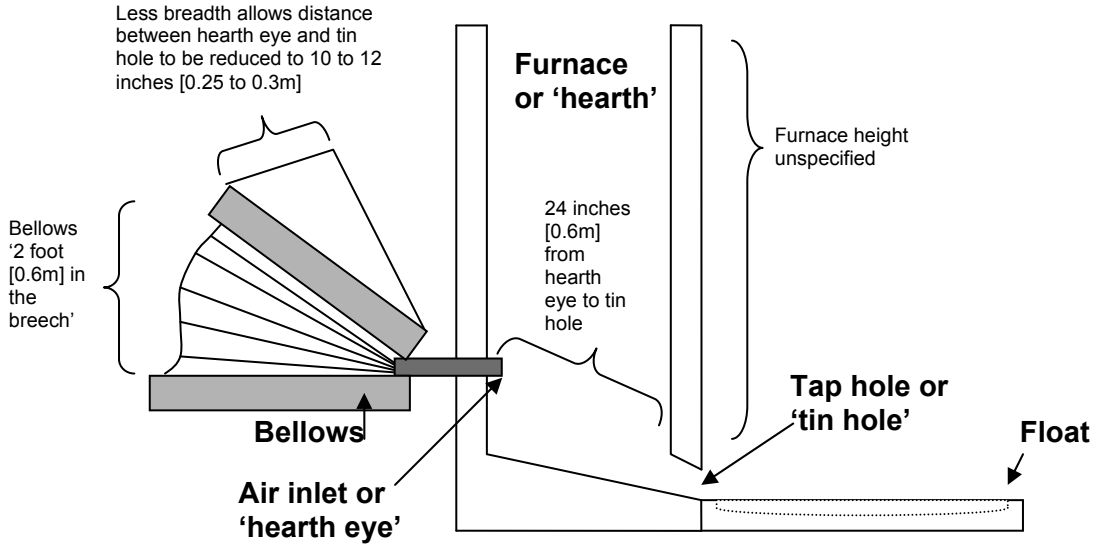


Figure 1.10: Simplified section diagram of a furnace or 'hearth' based on the account of Beare 1586 (not to scale)

Furnaces were pre-heated and black tin from alluvial and lode sources were smelted separately, as were different grades of each type of black tin; the coarsest grades first, with 'waste' last of all. (It is not clear what Beare means by waste: this could be the tails of the black tin from the buddle, or slag that is being recycled.) Black tin from

lodes, which had been more finely ground, required wetting before it entered the furnace, else it would be driven out of the furnace by the force of the blast.

In a period of 15 hours, the blower working for Beare obtained 408 lb (185 kg) of tin metal, from 13 foot of black tin (c.390 kg) [a foot was a measure of volume equivalent to 2 gallons; the mass of cassiterite it contained depended upon the grade of the ore concentrate, but was probably in the range of 24-36 kg (Carew 1602 p29)]. This represents a reduction in weight of about 50%. Molten tin exited the furnace through an opening - the tin hole - at the base of the furnace, and was collected in a shallow stone trough or 'flote' prior to being ladled into a mould.

If all went well during smelting, at least 300lb (136 kg) of tin metal could be produced in 12 hours: enough to fill a mould.

Carew's (1602 p29) account of smelting is briefer, but he reports that the black tin 'is melted with a charcoal fire, blown by a great pair of bellows moved with a water wheel, and so cast into pieces of a long and thick squareness, from three hundred to four hundred pound (136-182kg) weight'. On the subject of fuel, he notes the use of both wood and peat charcoal. The tinner wishing to have his tin ore smelted was responsible for the 'cost in buying the wood for this service …' Elsewhere he adds, 'The east quarters of the shire are not destitute of copsewoods, nor they of (almost) an intolerable price; but in most of the west, either nature hath denied that commodity, or want of good husbandry lost it. Their few parcels yet preserved are principally employed to coaling, for blowing tin. This lack they supply either by stone coal fetched out of Wales or by dried turfs, some of which are also converted into coal to serve the tinner's turn.'

Carew also gives some information on ore quality: a foot of moor-tin would weigh c.80 lbs (36 kg), compared to 52 lbs (24 kg) for mine tin, and 50 lbs (23 kg) for particularly

poor ores, and ‘Two pound of good black tin, being melted, will yield one of white: twenty eight or thirty foot of the best, forty, of the middle, fifty two, of the meanest, a thousand’, i.e. a thousandweight of tin metal (545 kg) would be produced from 28-30 foot volume of good quality ore (1008-1080 kg), but 40 foot volume of fair ore would be required, or 52 foot volume of poor quality ore (1196 kg).) As with Beare, a figure of about 50% reduction in weight from ore to metal is seen.

It is quite probable that in Carew’s time there were some improvements in the technology employed in the blowing houses. Queen Elizabeth, being eager to increase revenues from tin production, invited German miners to England to take advantage of their expertise, and it is likely that ore processing and smelting methods were also influenced by continental practice. Carew (1602 p26) records that Sir Francis Godolphin, one of the most renowned mine owners of the time, had ‘entertained a Dutch mineral man’, and subsequently developed the visitor’s ideas and ‘made tin with good profit of that refuse which the tinners rejected as nothing worth’.

The best account of German tin smelting is that given by Agricola (1556 p411-9), who provides a far more detailed description of furnace design and blowing technique than is to be found in any English work. (Other reports of tin smelting in Europe by Ercker (1574) and Barba (1637) are not as comprehensive as Agricola’s writings, though they agree in most respects.) The basic design of the furnace is shown in Figure 1.11.

Ore was fed into the furnace by the shovelful, followed by charcoal, layer upon layer. There were three different grades of ore, which would be smelted in furnaces of different dimensions if such were available (see twin furnaces in illustration in Agricola 1556 p417), the smallest grain size being placed in the widest furnace, and a gentler blast used. However, stream tin was best smelted in a furnace a palm-width wider than

was used for lode tin. If different furnaces were not available, the graded ores were smelted in turn and the blast strength varied.

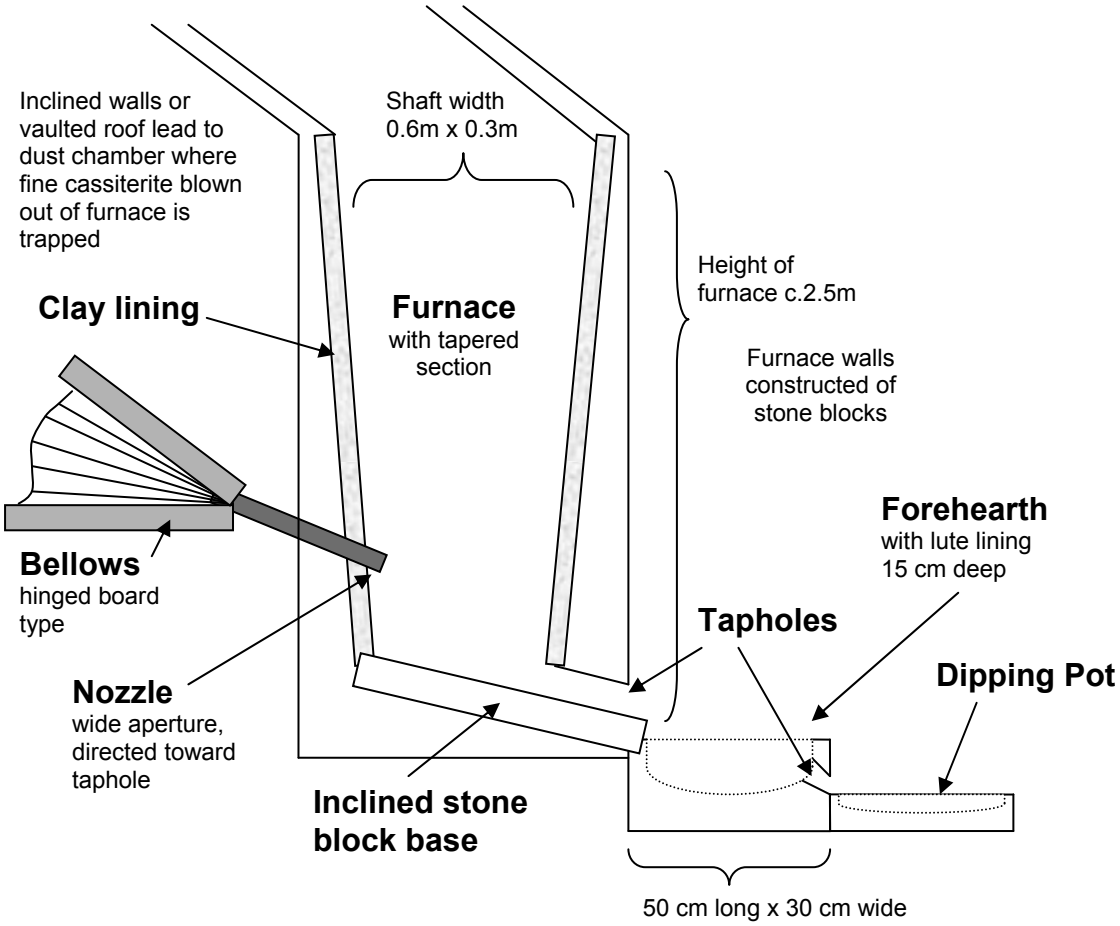


Figure 1.11: Section diagram of a German tin smelting furnace based on the account of Agricola 1556 (not to scale).

The furnace ran for three days and nights. As tin ran out of the open taphole into the forehearth (a collecting basin equivalent to the English float), the smelter scraped charcoal powder onto the surface, which encouraged the separation of slag and metal. The slag was scraped off the surface of the tin, and more charcoal added in sufficient quantity to cover the metal entirely so preventing re-oxidation.

The forehearth had its own taphole, which was periodically opened to allow the molten tin metal to be collected in a tapping/dipping pot. The tin, if judged pure, was poured

onto a copper plate, eventually forming a lattice of metal. The finished latticework bars are illustrated (p415) and appear to be over 1m long and about one fifth of that in width.

While the descriptions given by Agricola are helpful in interpreting the documentary and archaeological evidence for tin blowing in England, it is also clear that there were differences between English and German furnaces and the process of smelting (see Table 1.4).

Briefly, Agricola also mentions the furnaces used by the Lusitanians (Portuguese), which were of smaller size than those used in Saxony: his illustration shows a freestanding shaft furnace about the height of a man (Agricola 1556 p419). A pair of small manually-operated concertina bellows produced a relatively gentle draught. This arrangement made about half a centumpondium of tin in one day i.e. about 22 kg (1 centumpondium = 1 hundredweight).

After Carew, the next English account of tin blowing comes from Dr Cotton, in 1664, who describes how the black tin is 'cast together with Charcoals into a Furnace, as it melting, by the fire of a Wall-bellows; it flows out into a stone Trough and there they skim off the top of it, which is like black pitch, and is called Cynders: This they do not cast away, but stamping it again together with the Tin stones, it adds to the Quantity of the Tin… When the cynders are skimmed off, they put the tin into Moulds which contain about 3, 4, or 5 hundred weight a piece (136- 227 kg), and the burners mark is affixed on it.'

Dr Cotton's information on the amount of tin obtained from the ore is suspect. He states, '3 or 4 Gallons of the best black tin, usually makes one hundred weight of white Tin; this the Stanner buyeth of the owners at four pounds ten shillings the hundred

Table 1.4: A Comparison of 16th and 17th Century Blowing House Design and Details of the Blowing Process as given in Contemporary Accounts

Date	1556	1556	1586	1602	1664	1670
Location	Germany	Lusitania (Portugal)	Cornwall	Cornwall	Devon	Devon / Cornwall
Source	Agricola (trans Hoover & Hoover 1950)	Agricola (trans Hoover & Hoover 1950)	Beare	Carew	Dr Cotton	'Inquisitive Person'
Source type	Written account includes illustrations.	Written account includes illustration.	Written account.	Written account.	Written account.	Written account.
Material of construction	Rectangular blocks of sandstone or granite. Base stone 2 ft (0.6m) thick, 2 ft 9 in (0.8m) long. Interior coated with lute.	Not specified.	Not specified.	Not specified.	Not specified.	Clay.
Height	8 – 9 ft (2.4 – 2.7m)	Not specified. Estimated 5 ft (1.5m) from illustration.	Not specified.	Not specified.	Not specified.	Not specified.

Width **(back to front)**	2 ft (0.6m) at top; narrower at bottom.	Not specified. Estimated 1 ft (0.3m) from illustration.	24 inches (0.6m) 'from the hearth eye to the tin hole', but could be as narrow as 10 or 12 inches (0.25 to 0.3m).	Not specified.	Not specified.	Not specified.
Width (side to side)	1 ft (0.3m); narrower at bottom.	Not specified. Estimated 1 ft (0.3m) from illustration.	Not specified.	Not specified.	Not specified.	Not specified.
Method of Charging	From the top, through an opening in the side of the dust collecting flue above the furnace.	From the top (based on illustration) .	Not specified.	Not specified	Not specified.	Not specified.
Float	Forehearth lined with lute. 6 in (0.15m) deep, 1 ft 6 in (0.45m) long, 1 ft (0.3m) wide. Low wall on one side holding charcoal. Inclined floor to other side for overflowing slag to run down. Has sealed taphole leading to a dipping pot.	None shown.	Float named; text indicates its purpose collecting molten tin.	Not mentioned.	'A stone trough'; text indicates its purpose collecting molten tin and slag.	Float named; text indicates its purpose collecting molten tin.

Draught	Bellows of the hinged-board type situated at back of furnace. Translation implies multiple bellows. Wide aperture nozzles. Bellows nozzle enters through hole in furnace wall. Nozzle inclined down towards taphole. Bellows removed after smelting so furnace could be broken open at the back for repair.	Two manually operated concertina type bellows located at back of furnace.	Single bellows entering the furnace through the 'hearth eye', opposite the taphole. Distance between top and bottom board of bellows measured 2 ft (0.6m). Breadth was 24 in (0.6m), but could be reduced if the furnace was narrower.	Single bellows of large size ('a great pair of bellows') powered by waterwheel.	Single bellows; called 'wall-bellows'.	Not specified.
Flue	2 hood-walls above furnace leading to dust chamber or a vaulted roof supported by pillars, which has holes in it and dust chamber above.	None.	Not specified.	Some houses had none; tin dust caught in the thatched roof which was burnt off once every 7 or 8 years to recover it. The addition of a large sloping 'chimney' above the furnace was a recent development.	Probably none: reference to burning the blowing houses down to recover tin.	Not specified.

Fuel	Charcoal by the shovelful (total amount unspecified), layered with ore.	Not stated.	Not stated.	Wood and peat charcoal both used.	Charcoal.	'Moor tin' (alluvial cassiterite?) smelted with 'moor coal' (peat charcoal). 'Tin which lyes in the Countrey' smelted with mix of charcoal and peat. Charcoal for slag re-smelting.
Ore	Different grades smelted separately, either in different sized furnaces (a wider shaft for small grained ores and stream tin) or consecutively with varied draught strength. Amount of ore that could be smelted in 3 days depended on size of ore particles (large size took longer).	Not stated.	'Streamwork tin' and 'mine tin' smelted separately; largest pieces of stream tin smelted first, fine mine tin last.	Mine and stream tin both mentioned.	Not stated.	Implies alluvial and vein tin smelted separately, using different fuel.
Metallic tin output		About half a centum-pondium of tin per day (c.22 kg).	408 lb (185 kg) of tin metal from 13 foot of black tin (c.390 kg). 300 lb (136kg) could be produced in a tide.	A thousandweight of tin metal (545 kg) could be produced from 28-30 foot volume of good quality ore (1008-1080 kg) or 52 foot volume of poor quality ore (1196 kg). At least 300 lb (136 kg) produced in 12 hours.	One hundredweight (54 kg) of tin metal from 3 or 4 gallons (c.54 – 72 kg) of good quality black tin.	Not specified

Furnace operation	Smelting lasted three days. Small sized ore in wide furnace with gentle blast; large sized ore in narrow furnace with fierce draught. Metal flowing first from furnace was sign of a good yield to follow.	Not stated.	Smelting lasted a 'tide' (12 hours) or slightly more. Metal that flowed out of the furnace before the slag was considered poorer quality.	Not specified.	Ore and charcoal placed together in furnace.	Not specified.
Slag Recycling	Slags broken up with hammer or under wet stamps and re-melted with next batch of fine tin ore. Can be recycled up to 3 times.	Not stated.	Implied from the reference to 'sinder tin' being stamped with letter H to signify 'corrupt' metal.	Not specified.	Re-stamped.	Charcoal used for slag recycling.
Tapping and metal collection	Taphole always open. Metal collects in forehearth and separates from slag. Periodically metal allowed to flow into connected dipping pot.	Not specified.	Taphole called the tin hole.	Not specified.	Molten product flows into trough; slag is skimmed off. Tin cast into moulds holding 3, 4, or 5 hundredweight (136-227 kg).	'Mount egge' (hardhead) left at bottom of the float.

weight, but sells it at five pounds and upwards, to the Merchant and the hundred by which they sell it is one hundred and twelve pounds weight.' Using Carew's figures, a gallon of good quality ore would weigh 18 kg, thus 54 – 72 kg of ore would produce 54 kg of tin metal: a yield of 100 – 75%; clearly far too high.

The latest reference to blowing, before smelting technology took a completely new direction in the 18th Century, is that of the Inquisitive Person, who in 1670 stated 'that our Furnace is no other than an Alman Furnace' (i.e. a furnace similar to those in use in Germany, the design of which had not changed greatly since Agricola's time (Earl 1991)).

The writer proceeds to tell us that 'our Lime, though the strongest I ever yet heard of, as being made of the hardest Marble, will not endure the fire in our Hearth, but we must use a particular kind of Clay', and also that 'Moor-Tin (i.e. such as is digged up in the Moors) we find runs or melts best with Moor-coal, chark't; But our Tin, which lyes in the Countrey, runs best with an equal proportion of all Char-coal, and Peate for the first running: but when we come to remelt our Slags, then we use Char-coal.' (Moor tin probably means alluvial or eluvial cassiterite, and moor coal is peat; tin which lies in the country is probably vein ore.) 'When all is melted down and remelted there sometimes remains a different Slag in the bottome of the Float, which we term Mount-Egge; And that it is mostly an iron body, though of a Tin-colour, I assured myself by applying one of the Poles of a Loadstone to it, which quickly attracted it, yet not such a quantity by far, as that of Iron'.

This reference to 'mount-egge' is the first description of what appears to be the tin-iron alloy latterly known as hardhead; earlier writers only hint at its occurrence, remarking that certain substandard tin ingots were marked with the letter H, meaning

'hard tin' (see p143). The basic details of the tin blowing process are thus fairly well established. The furnace was preheated, using charcoal, and only when it had reached the optimum temperature were alternate layers of crushed ore and charcoal loaded into the top of the shaft, the fine ore being damped down to reduce losses through flying dust being driven off by the blast from the bellows. Different grades of ore were smelted separately, since they required different blast pressures, and the quality of the ore determined whether peat or wood charcoal was used: for the cleanest ores peat charcoal was favoured; for vein ores, which generally contained more impurities, a mix of peat and wood; and for high temperature slag reprocessing, wood charcoal alone.

As regards fuel use, several documentary sources lend support to contemporary descriptions of blowing. For example, in 1545 John Pencoste bought part of the coppice wood at Merthen, possibly for making charcoal for use at Retallack blowing house, which was on land leased from that manor (Henderson 1937 p121). There are 16th Century reports of Cornish charcoal burners being granted the right to go to Dartmoor to obtain peat turfs as a result of a shortage in Blackmore Stannary (Hamilton-Jenkin 1927 p72), a right that they may well have taken up, as Beare (1586 p38) reports that the Blackmore colliers carried their coals 30 or 40 miles, which, as Greeves (1992) points out, would put them on the edge of Dartmoor. There is also evidence for large quantities of wood charcoal having been imported into Cornwall by sea from the New Forest in the years up to 1695, some of which must have been utilized by the blowers (Hamilton-Jenkin 1927 p73).

Archaeological evidence for the fuels utilized for blowing is scant. However, at Upper Merrivale peat charcoal 'briquettes' were found within the tumble of the blowing

mill, and fragments of wood charcoal were noted mixed in amongst a sandy deposit that underlay the wall of the later stamping mill and was possibly a dump (Greeves 1992, 1993b, pers comm. 2002; Greeves and Passmore 1996). A single fragment of wood charcoal was also found embedded into a piece of slag (Greeves pers comm. 2002).

The amount of charcoal required to smelt a particular quantity of ore, the proportion of peat to wood charcoal used, and how much metal was obtained as a result, is not generally recorded for this period. Even where some information is given, uncertainties relating to the amounts recorded in the text (for example the mass of tin present in a foot of tin) make calculation difficult. Attempts to carry out such calculations (e.g. Earl 1985) are almost all based on data from later British furnaces and smelters overseas.

Archaeologically, the identification of a blowing house often depends upon the finding of slag - indeed some sites are only known from finds of slag. Slag has been located at about 30 sites that are thought to have been in operation during the Post-medieval period (see Catalogue of Smelting Sites). Unfortunately, almost all of this consists of surface finds, and for most sites it amounts to less than a kilogram. The one exception is the material from the excavation of the tin mills at Upper Merrivale (Gerrard and Greeves 1991, 1992a, 1992b; Greeves 1993b, 1995; Greeves and Passmore 1996; Greeves 1997): an estimated 12,000 pieces of slag were recovered from stratified contexts.

Documentary evidence makes it clear that waterwheels were used to power bellows providing the draught for the furnace, and though no waterwheels survive, there are many blowing house sites where either leats or wheel pits can be made out (see

Catalogue of Smelting Sites). Even where little remains of a building, the proximity to a suitable water supply is notable.

One consequence of using water-powered bellows was that ore would be blown out of the furnace and lost. This led to the practice of 'pulling down the house' in order to recover cassiterite dust. As Carew (1602 p26) puts it: 'During the tin's thus melting in the blowing house, divers sparkles thereof are by the forcible wind which the bellows sendeth forth, driven up to the thatched roof; for which cause the owners do, once in seven or eight years, burn those houses and find so much of this light tin in the ashes as payeth for the new building, with a gainful overplus.' The requirement to recover the tin dust from among the ashes of the thatch may have influenced the survival of the blowing houses in the long term, a roofless building being subject to more rapid decay than one that is complete.

By the 17th Century measures were being taken to collect the tin dust without resorting to such measures. Carew continues, 'Others do frame the tunnels of the chimneys very large and slope, therein to harbour these sparkles and so save the burning.' However, the building of flues for dust collection does not appear to have been universally adopted; Dr Cotton, writing in 1664, states 'In the melting of the tin some of the lighter parts of it are blown off, and stick in the several parts of the Blowing house, which they cannot well take off; And for that reason they seldome repaire those houses, but rather burn them, and the tin found in them will be sufficient to build a new house…'

As flues would have been dismantled in order to recover tin dust, their survival in the archaeological record is unlikely. However, a large amount of killas found in the area around the furnace of Upper Merrivale tin mill (SX55187665) suggested that

originally the furnace had some manner of superstructure (Gerrard 2000 p135), possibly a flue. Worth (1953 p314) suggested that there may have been a flue over the Lower Merrivale mill (SX55277535), on the grounds that the furnace wall was buttressed as if to support some great weight, while Earl (1991 p58) suggested that a flue may have been built into the short wall in the eastern corner of that mill.

Of the furnaces themselves, more might be expected to survive, but in fact there are very few examples in the field. Gerrard (2000 p135) lists the remains of seven on Dartmoor: Lower Merrivale, Upper Merrivale, Upper Yealm Steps (SX61716385), Avon Dam (SX67226553), Gobbett (SX64537280), Taw River (SX62059197) and Teignhead Farm (SX63778426). Newman interprets a structure at Week Ford (SX663723) as a furnace (Newman 1993), and at Yellowmead (SX57426755) and Glazebrook (SX66836031), although no furnace remains, floatstones can be seen (Worth 1933, 1953 p297, p308). The interpretation as furnaces of recesses in the walls of mills at Black Tor Falls (SX57497161 and SX57487162), Upper Yealm Steps, Mill Corner (SX59376676), Lower Merrivale, Week Ford, Henglake (SX655668) and Outcombe (SX58016860) by Worth (1889, 1953 p296-316) is doubtful.

Given the poor state of preservation of the small number of furnace remains that survive on Dartmoor (see p134), their dimensions can only be determined approximately, however the distances between the upright granite blocks forming the structure have been estimated as follows: Avon Dam 0.4m (Smerdon 1997), Lower Merrivale 0.5 - 0.6m (Worth 1892, 1931, 1953 p312) and Week Ford 0.8m (Newman 1993). However, examination of the furnaces at Avon Dam (Smerdon 1997) and Upper Merrivale (Gerrard and Greeves 1992a) has indicated that the furnace cavity was lined with clay, which reduces the shaft width. In the case of the Avon Dam

furnace, the lined shaft would be as little as 0.3m across, reducing to 0.17m at the base of the furnace (Smerdon 1997). Examples of possible furnace linings are rare in the archaeological record, but detached fragments of vitrified granite with a coating of slag, which may be pieces of the furnace wall, have been discovered at Week Ford, Upper Merrivale, Taw River and Stannon Brook (Greeves pers comm. Feb 2002). These samples will be discussed further in Section 3.3.

Documentary evidence suggests that the blowing houses of Devon mostly predate AD 1700; most of the surviving furnace remains probably date to the 16th or 17th Centuries. Unfortunately, there is no equivalent archaeological evidence for furnaces in Cornwall – none are known to survive – and it is necessary to rely upon a single documentary reference for information regarding furnace sizes. Beare's description of the blowing house furnaces of Blackmore Stannary in 1586 (p108) indicates that the distance between the single bellows inlet at the rear of the shaft and the front wall of the furnace was typically 0.6m, but that a smaller shaft width of c.0.25m was adequate if smaller bellows were used. These dimensions are thus widely consistent with the archaeological remains on Dartmoor.

The best-preserved example of a furnace is at Lower Merrivale (Worth 1892, 1931, 1953 p309, p312-4). It is composed of roughly worked granite blocks stacked to form three sides of a rectangular shaft 1.5m high, 60cm from side to side internally and 50cm from the back to the missing front wall (see Figure 1.12). One end of a granite float 60cm wide and 30cm thick, which is not now level, forms the base of the structure. The trough in the float stone is c.8cm deep, 33cm wide and at least twice that in length.

Figure 1.12: Remains of the furnace at Lower Merrivale blowing house (viewed from front), with upright side walls of granite blocks and a displaced float stone (F) forming its base (Ranging pole for scale = 1m)

The area behind the furnace is raised, with the blocks forming the back of the furnace set into this bank. This is probably where the bellows were situated. No trace of a wheelpit can be seen (Greeves 1996), so it is not possible to determine the relationship between the bellows and the waterwheel.

The furnace at Upper Merrivale blowing house only became apparent during excavation (Gerrard and Greeves 1991, 1992a, 1992b; Greeves 1993b, 1995; Greeves and Passmore 1996; Greeves 1997). The sides of the furnace, consisting of two granite blocks, were removed because they were unstable. The back of the furnace was lined with clay (Gerrard and Greeves 1992a). At the base of the furnace was a

slab of stone and a layer of clay furnace lining that contained a slagged fragment of the same material (Greeves 1995). The furnace showed no evidence of having been heated, and there was no coating of slag over the lining, implying it was abandoned before it could be used.

The furnace was constructed with its back against a massive granite boulder that had purposely been placed within a pit sunk into the floor of the building (Greeves and Passmore 1996). The upper surface of the boulder would have provided support for the nozzle of the bellows (Greeves 1995). A recess behind the furnace, containing a raised platform, probably housed the bellows (Gerrard and Greeves 1991), the wheelpit running alongside the blowing house wall, adjacent to the recess and furnace.

The excavations at Upper Merrivale clearly showed that there was more than one phase of rebuilding, both of the mill and the furnace within it. In addition to the slagged furnace lining at the bottom of the furnace, similar pieces were found built into the revetments in the northwest corner of the blowing house, along with burnt stone (Greeves and Passmore 1996). There is also a possible broken float stone placed upside down in the wall of the wheelpit. Another fragment of what may be a float lies together with a sundered mouldstone to the south of the adjacent stamping mill.

Another good example of a furnace is at Avon Dam blowing house, now normally submerged beneath the waters of the reservoir of that name. The blowing house was described by Parsons (1956), but although mouldstones were noted, the furnace was not recognized. More recently the building has been re-examined by Griffiths (1994) (who provides a photograph of the interior, including the furnace and what may be a float) and Smerdon (1997).

The furnace, constructed of vertically set granite blocks, is situated towards the middle of the building, and appears to have been freestanding. As with all other known tin smelting furnaces, the front of the structure is missing, and the sides of the furnace now stand only c.50cm high. The cavity between the blocks in the absence of an interior lining would be approximately 40cm, but a layer of refractory clay that can still be seen on the interior faces of the cavity reduces this to between 17 and 30cm. Smerdon notes that the amount of this material increases towards the rear of the structure so that it would have created a sloping base to the furnace, which would have encouraged the slag and metal to flow out of the taphole.

Unlike the arrangement at Lower Merrivale, the floatstone was external to the furnace: the furnace base is a flat block of granite, against which the floatstone would have rested. A shallow, broken trough that may have been the float is located about 2m to the north of the furnace. The cavity within the trough measures approximately 90 by 55cm and it is 12cm deep, thus making it somewhat larger than other Dartmoor floats. Smerdon expresses doubts regarding its identification; however the mouldstones from this site would give an ingot of over 100 kg, which is at the heavier end of the spectrum for Devon moulds.

The wheelpit was probably on the southeastern side of the blowing house, so that the bellows may have been located in the southern corner of the building, behind the furnace.

Although no definite furnaces are presently known from Cornwall, Gerrard suggests that a raised platform within the southern part of the blowing house at Retallack (SW732297) may have been associated with the furnace (Gerrard 1985). A displaced

floatstone has been found at Treswallock (SX105781) on Bodmin Moor, but no blowing house is known at this location (Herring 2005).

Around 30 mouldstones associated with Post-medieval blowing houses survive in the archaeological record (see Catalogue of Smelting Sites). The majority are located on Dartmoor and have been described by Worth (1892, 1914, 1932, 1933, 1938, 1953 p291-307) and other antiquarian investigators (Kelly 1866; Amery 1870; Crossing 1891-2; Burnard 1888, 1889), while more recent examinations were carried out by Parsons (1956), Gerrard (1985, 1986 p149, 2000 p137-8), Greeves (1991, 1992, 1994, 1996b, 2004), Newman (1993) and Smerdon (1997).

Post-mediaeval mouldstones are (with the sole exception of a mould from Yellowmead, which is carved out of elvan (Worth 1953 p307)) blocks of granite – some indeed are large boulders – usually with one, but occasionally two, cavities carved into them. Mould cavities are roughly rectangular in plan, with inclined sides so that the area of the base of the cavity is smaller than the area around the rim. The sides and base are generally flat, although repeated heating causes them to become more concave as the granite flakes away. Greeves (1981b) does, however, report seven instances of moulds, distributed across five sites, which have a central ridge across the base of the mould, so forming a groove in the finished ingot, perhaps for ease of transport. These include two examples at Upper Yealm Steps. The presence of these projections led Worth (1892) to suggest that the moulds would produce an ingot of the 'well known astragalus shape', and indeed the top of the finished ingot would have appeared to be formed into an H. However, the ridges are not well-developed and would produce an indentation that is confined to the underside of the ingot. Thus, as Beagrie (1983) notes when writing of the H shaped St Mawes ingot, it would not

do to ‘over-stress the resemblance’ between that ingot and the Dartmoor ridged moulds.

Figure 1.13: Mouldstone at Lower Merrivale tin mill (notch at edge of cavity indicated by arrow) (Scale bar = 15 cm)

The size of some of the blocks used as mouldstones makes it unlikely that they were tipped in order to remove the ingot, and another feature seen on some Devon mouldstones (e.g. at Colleytown, Upper and Lower Merrivale, Lower Yealm Steps, Retallack and on two stones at Avon Dam) gives a clue as to how this was accomplished. Carved into one short side of the mould-cavity is a notch (see Figure 1.13), which, it is thought, supported a stick of green wood or an iron bar that lay diagonally across the middle of the mould thus producing a hole through the solidified block (Worth 1953 p314; Greeves 1981b; Earl 1991), like that exhibited by the ingot from Fowey harbour (Rogers 1903; Penhallurick 1986 p225-7).

Several sites have mouldstones that have one or two smaller cavities, generally referred to as sample moulds, cut into the rim beside the main mould, see Figure 1.14.

Greeves (1981b) states that sample moulds are known from twelve sites. The possible function of these cavities is discussed in Section 4.4 (p461).

Figures 1.14a and b: Mouldstones at Upper Merrivale tin mill (sample moulds indicated by arrows) (Scale bar = 15 cm)

Estimates of the mass of tin that a mouldstone could hold have been made by Worth (1953 p291-307) and others. These determinations, coupled with information deriving mainly from coinage records and contemporary descriptions of smelting that give an indication of ingot size, make it clear that there was no standard ingot. This was not necessary, since blocks of tin were sold by weight. Worth (1953 p316) notes that at the Michaelmas (September 29th) Coinage of 1595, the average weight of an ingot in Chagford Stannary was 197 lb (89 kg), while at Ashburton ingots averaged 168 lb (76 kg). In addition to Worth, the subject of ingot size has been considered by Greeves (1981a, b) and Gerrard (2000 p136-8). The available data shows that through the 16th and 17th Centuries the trend was towards larger ingots, but as a rule ingots from Devon were smaller than Cornish ingots of the same date. Whereas the average for a Cornish ingot in the 15th Century was 200-250 lbs (90-114 kg) and in Devon 100-120

lbs (45-55 kg) (Greeves 1981b), in the latter half of the 16th Century Beare (1586 p107) notes that 300 lb (136kg) of tin could be produced in a tide of 12 hours; at the turn of the century Carew (1602 p25) states that a tin ingot weighed 'from three hundred to four hundred pound (136-182kg)'; and by the mid 17th Century, the tin was put 'into Moulds which contain about 3, 4, or 5 hundredweight (136, 182, 227 kg)' (Cotton 1644), while by contrast the ingots from Devon in the 17th Century were usually in the range of 200-250 lb (90-114 kg) (Greeves 1981a). However, in 1625 records from the Stannary Convocation refer to tin cast in pieces, slabs and spoonfuls of over a pound in weight (Brooke 1998 p63), so a great deal of variation in the weight of tin presented for coinage could apparently occur.

Few ingots of this date survive (see Catalogue of Tin Metal Finds). Five ingots, with masses between 149 kg and 167 kg, that were dredged from Fowey Harbour (Rogers 1903; Penhallurick 1986 p225-7) possibly date to the late 15th Century; only one is still in existence. The possibility that the Trereife ingot is of Post-mediaeval date has been discussed previously (see p62).

In addition to these, antiquarian writers mention finds of tin metal that may be attributed to this period; claims of great antiquity made by the authors are probably a serious overestimate. One, discovered in the 1830s by Edmund Pearse, was reported thus: 'In and about the old stream works there are now to be seen several remains of the Phoenician smelting houses, called by the miners Jew's Houses: from one of these, near the confluence of the of the East and West Dart (c.SX6774), about three years since, there was taken tin ore… and not far from this place there was found a block of Jew's tin, supposed to be the oldest in existence, and now in the possession of a gentleman of this town. The surface of this block betrays marks of great

antiquity, being much corroded by the influence of those external agents to which it has been exposed' (Bray 1836 Vol 3 p254). As no further information is given regarding the find it is not possible to say whether this was a true ingot or an accumulation of escaped metal. It has been suggested that the building in question may be Week Ford blowing house (SX663723) (Newman 1993), but it could equally refer to the much less well-preserved mill at Dartmeet (SX672739) (Greeves 1981a).

Opie (1932) briefly notes the discovery of an ingot in a 'Jew's House at Newton Moor near Condurra' in Cornwall. (Newton Moor was a mine later renamed Wheal Grenville (SW665387), which was part of a group of mines that included Condurra or Condurrow (West Briton and Cornwall Advertiser, 7 July 1887).) This ingot was melted down, but was described as being H shaped, thus may have been similar to the St Mawes ingot, or to the ingots that would have been produced in ridged moulds such as those at Upper Yealm Steps.

What was described as a 'Regular H-shaped ingot.' was found at Slade House, Cornwood (c.SX5068) (Rowe 1896 p175; Penhallurick 1986 p118). This ingot, which weighed 23 kg, was reported as fitting the mould at Lower Yealm Blowing House. It no longer survives.

As these ingots have not been subjected to chemical analysis, it is not possible to comment upon the quality of the metal they contain.

Tin produced in this period appears to have been of variable quality, to the extent that measures were taken to distinguish between pure tin and contaminated metal. Beare (1586 p32) describes how blowers were required to take oath 'that they shall not assent to the making of any corrupt metals, so that every one of these ought to have upon them there several letters, which must be set overthwart the piece of tin contrary

to the blowing house mark and owners of the tin mark. Hard tin must have this letter: H; Sinder tin the letter S; Pillion tin this letter: P. Then is there another kind of tin, called Relistian tin, which must have upon it this letter: R. These four marks of corrupt tin every blower of a blowing house ought to have in a readiness at their blowing houses.' Hard tin probably refers to tin contaminated with iron, which forms the tin-iron alloy known in later times as hardhead. Pillion tin refers to prills of tin recovered from the crushed slag (defined by Pryce (1778 p325) as 'tin which remains in the scoria or slags after it is first smelted, which must be separated and remelted). Sinder tin probably refers to the tin obtained when slags were returned to the furnace and resmelted at a higher temperature; such tin is later referred to a slag tin (Louis 1911 p24). Relistian tin may have been a general term for tin containing metallic elements such as arsenic (see p459).

Carew (1602 p27) also makes mention of Hard tin (see p144) but not the other varieties listed by Beare, while the Inquisitive Person in 1670 remarks upon the production of what must surely be the tin-iron alloy hardhead as a by-product of smelting (Anon 1670).

In 16th Century Germany different stamps were used to mark the tin bars to distinguish between tin smelted from cassiterite from alluvial and lode sources (Agricola 1556 p415).

In England, ingots of tin, once produced and stamped in accordance with Stannary law, had then to be taken on the appointed day to the nearest Coinage town, where the quality of the metal would be assessed and duty paid upon it, at which point the tin was legally freed for sale. Carew (1602 p27) provides the first contemporary descriptions of the coinage process as it occurred at the beginning of the 17th Century:

‘For the manner of the coinage, the blocks or pieces of tin are brought into a great room ordained for that purpose, and there first peized [weighed], then tasted, that is, proved whether they be soft tin or hard, and after marked with her Majesty’s stamp. To the hard (less worth by fifty shillings in the thousand than the soft) the letter H is added ere it comes from the blowing house. Each thousand must answer 40 shillings to the Queen, which, with other incident fees being satisfied, then and not before, it is lawful for the owner to alienate and distract the same’. Tin that was found to be substandard or ‘hard’ was worth between 2 and 20 shillings per hundredweight less.

A later account by Dr Cotton (1664) differs little: ‘It is then called white Tin, and is from the Blowing house carryed to the Coynage where being poised and tested, that is examined by cutting of parts, whether it be pure and soft, then it passes without Tarring, and the Kings Stamp is set on it…’.

The tradition of coinage continued for nearly 2 centuries after Dr Cotton set down his observations, but changes in the way tin was smelted were only four decades away.

1.4.7: The 18th and 19th Centuries (AD 1700 to AD 1900)

1.4.7.1: Production from the 18th Century

At the beginning of the 18th Century all tin was smelted in shaft furnaces in traditional blowing houses, but the first decade of that century saw the appearance of a new type of tin smelting furnace – the reverberatory smelter – that would eventually supersede the blowing house as the preferred method of smelting tin, though the demise of the blowing houses took nearly 150 years to come to pass. This new method of smelting both took advantage of, and prompted, many improvements in mining and ore processing technologies. As a result, the amount of tin being produced increased to a level never seen before.

Coinage records continue to be a useful source of information regarding the annual output of tin in this period. They indicate that by the 1700s, tin production was concentrated in western Cornwall, centred on the coinage towns of Truro and Penzance (Brooke 1998 p275). Separate coinage figures are available for the counties of Cornwall and Devon until 1750; these have been summarized by Lewis (1908 p259-64), and show production in Cornwall increasing steadily, and far outstripping production in Devon (see Table 1.5 and Figure 1.15). Indeed, production in Devon, which between 1691 and 1714 had been experiencing a small-scale boom with a peak output of 123,000 lbs (55,910 kg), declined so precipitously that by 1731 no tin was being smelted in the county (Lewis 1908 p257; Greeves 1992), and resumption of work in the 1740s produced at best 6,000lbs (2,730 kg) of metal in a year (Lewis 1908 p257).

Though exact figures for production in Devon between 1750 and 1838 are lacking, output having been combined with that of Cornwall, information gleaned from a range of other documentary sources point to a recovery beginning in the last quarter of the

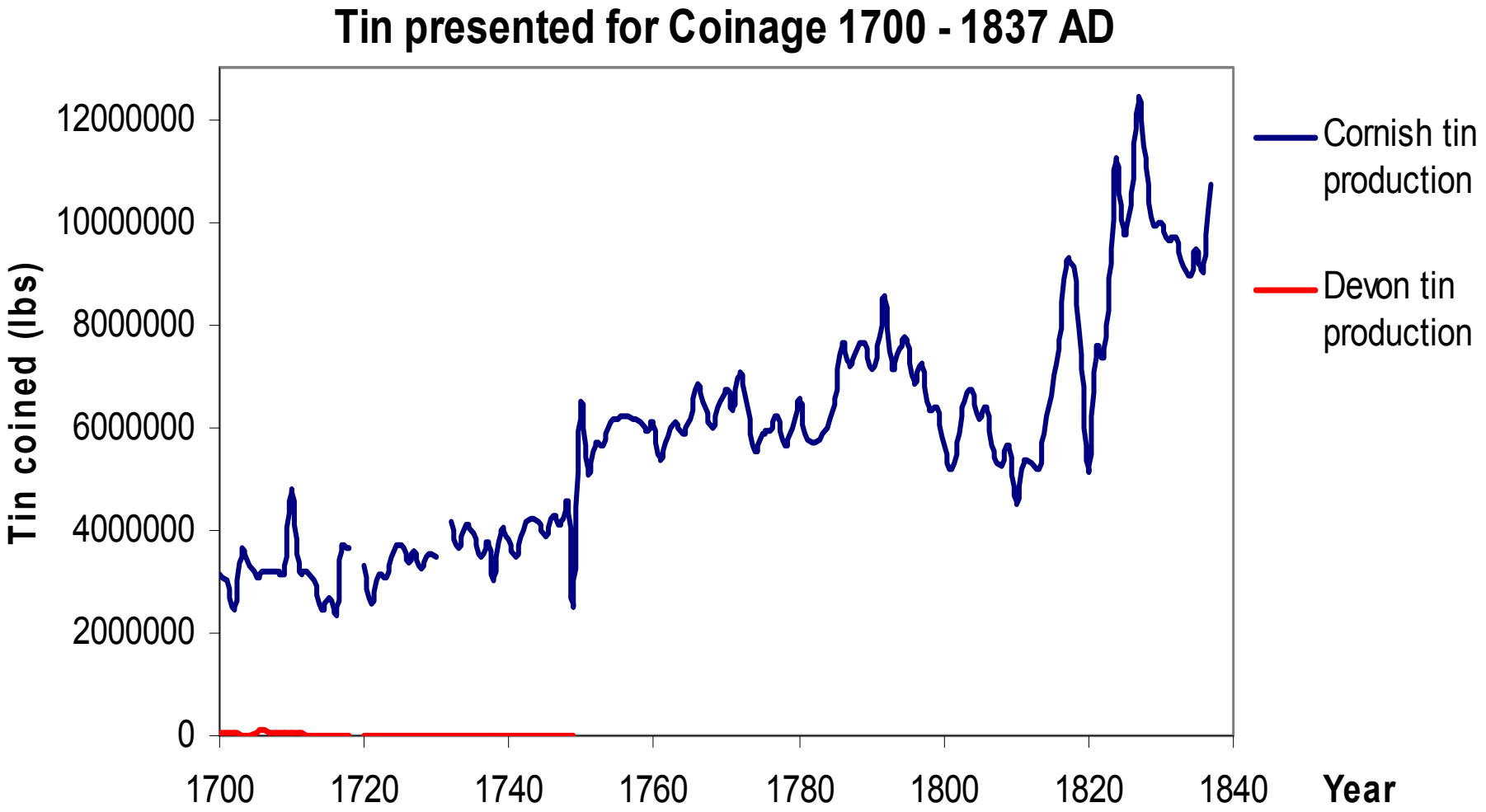


Figure 1.15: Amount of tin metal coined in Devon and Cornwall between 1700 and 1837 (data from Lewis 1908)

18th Century and lasting until the 1830s (Greeves 1996). Cornish output reached a peak around 1780, declined slightly around the turn of the century, but afterwards rose to hitherto unmatched levels.

Table 1.5: Tin Coined in Devon and Cornwall in the 18th and 19th Centuries (Data from Lewis 1908 p256-8)

Year	Tin Coined in Cornwall	Tin Coined in Devon
1700	3151504 lb (1432502 kg)	47384 lb (21538 kg)
1720	3302440 lb (1501109 kg)	5464 lb (2484 kg)
1740	3795578 lb (1725263 kg)	0 lb (0 kg)
1760	2717 tons (2464862 kg)	
1780	2926 tons (2654467 kg)	
1800	2522 tons (2287958 kg)	
1820	2290 tons (2077488 kg)	
1837	4790 tons (4345488 kg)	

The coinage system was abolished in 1838. Later production figures were compiled by the Mining Record Office, and published in annual volumes as 'Mineral Statistics of the United Kingdom of Great Britain and Ireland'.

Ore output from 1852 to 1913 for Devon and Cornwall has been summarized by Burt et al (1984 Table 1, 1987 Table 5), and shows that Devon continued to produce a small quantity of tin (amounting to approximately 1% of the total UK output) for much of the remainder of the 19th Century, and into the 20th, with 97 tons (87,998 kg) of tin ore being recorded as late as 1913 (Burt et al 1984 Table 1). By contrast, Cornish ore extraction increases steadily up to 1871, peaking at 16,759 tons (15,203,765 kg) – equating to a metallic tin output of 10,900 tons (9,888,480 kg) (Hedges 1969 p13) – falling off very slightly thereafter but remaining relatively stable at around 13,000-14,000 tons (11,800,000-12,700,00 kg) for the rest of the 19th Century, then after

suffering another fall in 1896, stabilizes once again at around 6,000-7,000 tons (5,440,000-6,350,000 kg) (Burt et al 1987 Table 5).

With increasing industrialization, the costs and capital outlay involved in setting up and maintaining smelting furnaces escalated; from the 18th Century there is a shift to ownership by partnerships and companies owned by shareholders. Business records and accounts provide much information regarding smelting houses and the workings of the tin trade at this time. An overview of the subject has been provided by Barton (1967, 1968, 1971).

1.4.7.2: Ore Extraction

Documentary evidence makes it clear that lode ores were providing an increasing majority of the ore for tin smelting. In Cornwall, in coastal areas, particularly in the Penwith and St Agnes mining districts, there was exploitation of cliffside outcrops. Pryce (1778 p20) refers to mines 'at or near the sea cliffs'.

Many more shaft mines were opened, and with advances in pumping technology to remove water from the lower levels – notably the introduction of the steam engine in the second decade of the 18th Century, and plunger pattern pumps in 1810 – these were delved to ever-greater depths. Collins (1912) and Dines (1956) provide extensive lists of hundreds of Cornish mines, not all of which were purely for tin.

After c.1700 deep mining using shafts and adits appears to have been preferred over opencast methods in Devon (Greeves 1981b; Gerrard 1997 p104). This was on a far smaller scale than in Cornwall, but around 50 tin mines are known to have operated in the 18th and 19th Centuries (Dines 1956; Harris 1968 p26, p45).

Despite the growth in shaft mining, alluvial deposits continued to be exploited through into the 20th Century. Streamworking clearly remained of sufficient importance to merit inclusion in the works of Pryce (1778 p131-5), Borlase (1758 p161) and Hitchens and Drew (1824). Even in 1855 Leifchild (p202) records that 'Although the richest deposits have been well worked, and the ground turned over probably twice or thrice, the tin stones rejected at one time becoming valuable at another from their comparative scarcity, yet there remains still enough to prevent tin streaming from becoming extinct in Cornwall' and twenty years later Collins also describes the practice (1875 p33).

Higgans (1979) draws attention to the Angarrack Smelting House (SW583382) coinage books, which survive up to 1741 and record the receipt of stream tin (Bolitho Records DDRG 1/122-7 CRO). Henwood (1873/4) reported that in 1873 the total output of stream tin from Cornwall was 50 tons (45360kg).

A Bodmin Moor resident has reported that streaming was carried out by farmers, working part-time during the quieter times in the agricultural year, up until the late 19th Century (Gerrard 1987), and streamers working at Red Moor (c.SX0661) were photographed some time at the beginning of the 20th Century (Embrey and Symes 1987 p16).

Streaming in Devon appears to have been limited in this period, but recorded examples include 'Rendals Streamworks' at Rundlestone (SX579750) in the 1790s (Greeves 1994), and 'Wheal Providence' in the parish of Sheepstor (c.SX5667) in 1815 (Cook et al 1974).

Further support for the use of both types of ore, at least within the 18th and early 19th Centuries, comes from contemporary accounts of smelting which make it clear that

mined ore and alluvial cassiterite were often smelted using different techniques (see p154).

The old rules that prohibited the removal of black tin from the Stannary in which it was raised were no longer in force by the 18th Century. Although it is likely that the small amounts of black tin raised by streamers would still be sold to local smelters (Barton 1968 p140), ores were sometimes transported long distances. Examples are provided by Henderson (1912), who gives a list of parishes and individual mines that provided ore for the Newham Smelting Works (SW829441) in 1707, and Barton (1968 p140) quotes similarly long lists of mines that supplied Calenick Smelting House (SW820440) near Truro in 1829 (Account Book of Tin Bought, Calenick, 1828-36, DDRG 1/150/61 CRO) and Trereife Smelting House (SW455294) near Penzance in 1890 (Trereife Black Tin Purchases Book 1883-91 DDRG 1/114 CRO). Greeves (1996) notes the following examples of ores being taken from Devon into Cornwall: records exist showing ore going from Vitifer Mine (c.SX6881) to Calenick Smelting House in 1791 and 1798 (CRO/DDRG 1/128-141, June 23 1791; CRO/DDRG 1/128-141, 6 April 1798), from Vitifer to Penzance in c.1797 (DRO 564/Vol 16, p1), and from Whiteworks Mine (SX612710) to Calenick in 1790 (CRO/DDRG 1/128-141, 7 July 1790).

Although restrictions on the movement of tin ores between districts had been lifted, the export of British tin ores was still prohibited (Leifchild 1855 p203). However, some ores were beginning to be imported from abroad; Leifchild (1855 p213) refers to Malaysian ores.

From 1859 onwards, Bolivian ores were bought for smelting at Charlestown (SW82064494) (Barton 1967 p129). Good quality Bolivian ores could assay as high as

72% metallic tin (compared to 62-65% for Cornish ores) (Thibault 1908 p190), but contained impurities that made them troublesome to smelt, with the result that other companies that purchased South American ores initially lost money (Barton 1967 p129; 1968 p142). Later, only the better quality ores were smelted in Cornwall, poorer grades being sent to Germany (Thibault 1908 p190). Ores from Australia were also smelted at Charlestown (Charlestown Shipwreck & Heritage Centre 2006).

1.4.7.3: Ore Processing

Ore processing continued to be a requirement. Leifchild (p204) reports that in 1855, larger pieces were broken up using hammers and then the ore was crushed using stamps. The wooden stamping machinery illustrated by Borlase in 1758 (Plate XIX), and the descriptions of stamps and stamping given by Pryce in 1778 (p328) and the writer who visited a mill near St Ives in 1780 (Swete 1971), do not appear markedly different from the stamps of the previous century. However, refinements in the design of stamping and dressing machinery did occur: mortar stones went out of use in the 1700s, being replaced by composite rubble heads (Gerrard 1997 p92); around 1805, waterwheels were replaced by steam engines (Earl 1991); and, by the second half of the 19th Century, Californian stamps were being introduced, which were much more effective as they had a stamp head that rotated as it hit the ore (Gerrard 1997 p92). There was also a move towards having separate stamps and smelting houses (Brooke 1998 p49), so that dressing of the ore often took place at the mine and the resulting concentrate would subsequently be sold to an independent smelter (Leifchild 1855 p203; Earl 1991).

The dressing of the crushed ores also benefited from a range of new developments, including the circular buddle, tossing tubs, trunking boxes and shaking tables (Gerrard

1997 p92). The details of these are beyond the scope of this work (Leifchild 1855 p204-7 gives a summary); suffice to say that the dressing process became more efficient.

In 1792 batches of black tin assayed at Calenick were said to contain between 45 to 63.7% tin. Complaints were lodged regarding the poor quality of those lower yielding batches (Tylecote 1980a).

In the opening years of the 20th Century, Cornish ores were being dressed to produce concentrates containing between 79 and 82% tin oxide (62 to 65% metallic tin), the main impurities being silica, iron oxides and some tungsten (Thibault 1908 p190).

One of the difficulties arising from the ever-increasing demand for cassiterite was a decline in ore quality. Ores that were not 'clean', i.e. were composed of cassiterite mixed with various other chemical species, had previously been rejected on the grounds that it was either not possible to remove these impurities, or that it was not economically viable to do so.

It is true that good quality ores were still obtainable in the 18th and 19th Centuries (e.g. ores from Eylesbarrow Mine (SX5968) (Cook et al 1974) and the vein ores of the St Austell area (Barton 1967 p25; Hamilton-Jenkin 1967 p9 quoting Philip Rashleigh MSS, Catalogue 1797 RIC)), and Leifchild (1855 p204) reports that 'From rich veins a large proportion of the ore is obtained in a pure state, and then it is only necessary to break down the large irregular masses into fragments of a tolerably equal size to render it fit for the furnace'. However, by the 18th Century, it was considered necessary to attempt to clean and utilize poorer grade ores – black tin that was, according to Leifchild (1855 p208), 'associated with iron, copper, and arsenical pyrites, and with wolfram', and new methods were developed to accomplish that.

Sulphide minerals containing species such as arsenic, cadmium and lead could be roasted in an oxidizing atmosphere – a process known as calcining – and the majority of the contaminants would be driven off as vapour (Thibault 1908 p146; Wright 1982 p64; Smith 1996). The practice of calcining tin ore in tin kilns was established in the 17th Century, and was first described by The Inquisitive Person in 1670 (Anon 1670) (see p116). During his visit to Cornwall in 1725, Kalmeter noted that 'In St Agnes mining district they recently started to burn or roast the ore …in a lime kiln, particularly if it is hard, as afterwards it is much easier to stamp. … In the places and at those mines where the ore is mixed with mundic or sulphur pyrites it must first be roasted and these impurities must be completely burnt out, for which they have their burning houses or calcining houses, and furnaces'. He then went on to describe a burning house and the process of calcining (Brooke 1998 p50, p341). Hitchens & Drew (1824 p618) report that 'About four fifths of the ore raised from mines is infected with mundic; in consequence of which it must be purified in the burning house...'

A very well preserved example of such a building is the 'blowing house' at Godolphin (SW60333205), which has the date 1784 inscribed on a stone on one wall, and is described as a 'burning house' on the estate maps of 1786 (CRO RH 210). Schofield (1968) provides a detailed description of this building, while misinterpreting its purpose.

Impurities other than arsenic and sulphides were not so easily handled. Calcining was not effective in eradicating tungsten and bismuth, nor would it remove iron minerals.

By the mid 19th Century chemical methods of separating impurities from ore had also been developed. Leifchild (1855 p208) notes that a 'new process' could thoroughly clean ores containing tungsten minerals (Thibault 1908 p154), though this was only

available to the larger operators for economic reasons. Tungsten, which previously had reduced the value of the tin ore, thus became a saleable commodity in itself.

From about the 1840s ores containing iron oxides were cleaned by leaching with acid (Barton 1967 p91), as were calcined copper bearing ores (Thibault 1908 p156-7).

While these methods of treating tin ores were highly successful, the variation in quality of tin concentrates led to their being smelted in slightly different ways.

1.4.7.4: Smelting in the 18th and 19th Centuries

The traditional blast furnace continued in use throughout the 18th Century - indeed the last blowing house did not close until about 1860 - but increasingly the newly-developed reverberatory-type furnaces (see p164) were utilized.

It was not unusual for a smelting works to have both reverberatory and blast furnaces on site. However, documentary sources, such as the report by Henric Kalmeter, a Swede who in 1724-5 made a two month long tour of the industries of the south west of England, recording his observations in a diary (Brooke 1998, 2001), imply that while a smelting works with both types of furnace might have multiple reverberatory furnaces in operation, a single blowing house was apparently deemed sufficient (Brooke 1998 p66).

Each type of furnace was considered to have its own strengths. Reverberatory furnaces had larger capacities, could cope with lower quality ores, and had lower fuel costs per unit mass of tin produced. Blowing houses, meanwhile, were suited to the production of the purest grades of tin. Known as grain tin, this was usually smelted from stream tin (Pryce 1778 p137; p322; Leifchild 1855 p210). There was no hard and fast rule, however. Some lode ores, if they were of high quality, were smelted in blowing houses.

That such ores occurred in the St Austell area, in addition to rich alluvial deposits, accounts for the fact that it was there that the last three blowing houses operated (Barton 1967 p25).

The Blowing House Blast Furnace

Furnace Design

Several descriptions of 18th and 19th Century blowing houses are available and reveal that despite the fact that the blowing houses were increasingly being replaced by reverberatory furnaces, blast furnace design continued to be refined. A summary of the features of the 18th Century furnaces are provided in Table 1.6.

The earliest 18th century account of blowing houses is that of Kalmeter in 1724-5. He described blowing houses in terms best translated as breast furnaces (Brooke 1998 p66, p347). The body of the furnace was made of granite and it stood 5 feet (1.5 m) high in total, of which 3½ feet (1 m) of the front wall, or breast, was removable. This breast portion, which was newly built for each smelt, was also of granite and was lined with clay, making it three inches (8 cm) thick. The shaft measured 2 feet (60 cm) from the back wall to the front, while between the sidewalls it was 2 feet 4 inches (70 cm) wide at the top, tapering down to 2 feet (60 cm) at the base. The small taphole at the very base of the furnace was kept constantly open, allowing molten metal and slag to run out into a trough as soon as it formed.

At the top, the shaft was walled in, with a chimney or flue set to one side of the shaft, so that its opening was above the level of the breast. This flue led away from the blowing house, apparently rising gently for some considerable distance up a hillside –

Table 1.6: A Comparison of 18th Century Blowing Houses from Contemporary Descriptions

Note: As no scale is provided for the illustrations by Raspe, approximate relative dimensions have been provided in arbitrary units.

Date	1725	1778	1796	Late 18th Century
Source	Kalmeter	Pryce	Hatchett	'Raspe'
Source type	Written account	Written account	Written account includes thumbnail sketch	Diagram including elevations, plan and section
Material of construction	• Granite • The front portion was a removable granite slab which was lined with clay when replaced	• All made of moorstone (i.e. granite) and clay, well cemented and cramped together	• Granite	• Not specified • Regular blocks c.30cm high are illustrated • Front portion of shaft not built of blocks as is the rest of the structure
Height	5ft (1.5m)	6ft (1.83m)	9-10ft (2.75 to 3m)	Not specified 13 units
Width (back to front)	2ft (60cm)	2ft (60cm) at top 14 in (53cm) at base	Not specified Had 'a double cone' shape, i.e. with a fattened waist.	Not specified Cone shape; wide at top, narrow base 7 units internal at top 4 units internal at base
Width (side to side)	2ft 4 in (70cm) at top 2ft (60cm) at base	2ft (60cm) at top 14 in (53cm) at base	Not specified	Not specified
Method of Charging	Not stated	Not stated	Hatch in side wall, about half way up the shaft	Not specified

Tap hole	• Hole at base	• Hole at base • Text implies open during smelting • 4 in high (10cm) 1½ in wide (4cm)		Not specified
Float	• Trough present	• Moorstone float • Length 6½ft (1.98m) • Width 1ft (30cm)		• Float consists of channel in ground at the front of the furnace • 14 units long 3 units wide
Draught	• Bellows (number unspecified) • Length 5ft (1.5m) Max width 3ft (90cm) • Nozzle width 6 in (15cm) • Water powered	• Two bellows • Length 8ft (2.45m) Max width 2½ ft, (0.76m) • Nozzle fixed 10 in (0.25m) from base of furnace through wrought iron 'hearth-eye' • Water powered	• Two bellows • Water powered • Cylinders used instead of bellows at some furnaces	• Two bellows • Length 24 units Max width 12 units • Nozzles inclined downward • Nozzles enter back of furnace; thus situated opposite tapping hole • Water powered
Flue	• 45ft (14m) flue • Set to one side of the shaft • Leads to external building	• Not specified	• Inclined flue 20 fathoms (36m) long • Extends from the conical top of the shaft • Leads to external circular building	• Inclined flue (initially inclined downward, then horizontally, then vertically upwards) • Extends from the top of the shaft • Collection chamber at top of hill

the example that Kalmeter saw had a flue 45 feet (14 m) in length – where was constructed a small stone building that allowed the smoke to issue from its doorways while keeping rain out of the flue.

The draught for the furnace was supplied by bellows, which were reliant on waterpower. These measured 5 feet (1.5 m) in length and had a maximum width of 3 feet (90 cm). The copper nozzle of the bellows was relatively wide: 6 inches (15 cm).

Half a century later, a description is given by Pryce (1778 p136): 'The furnace itself for blowing the Tin is called the Castle, on account of its strength, being massive stones cramped together with Iron to endure the united force of fire and air. This fire is made with charcoal excited with two large bellows, which are worked by a water wheel… They are about eight feet long (2.45 m), and two and a half (0.76 m) wide at the broadest part. The fire place, or castle, is about six feet (1.83 m) perpendicular, two feet (0.60 m) wide in the top part each way, and about fourteen inches (0.53 m) in the bottom, all made of moorstone and clay, well cemented and cramped together. The pipe or nose of each bellows is fixed ten inches (0.25 m) high from the bottom of the castle, in a large piece of wrought iron called the Hearth-Eye. The Tin and charcoal are laid in the castle, stratum super stratum, in such quantities as are thought proper; so that from eight to twelve hundredweight of Tin, by the consumption of eighteen to twenty-four sixty gallon packs of charcoal, may be smelted in a tide or twelve hours time. Those bellows…throw on a steady and powerful air into the castle; which, at the same time that it smelts the Tin, forces it out also through a hole through the bottom of the castle, about four inches (10 cm) high, and one inch and a half wide (4 cm), into a moorstone trough six feet and a half (1.98 m) high [sic], and one foot wide (0.30 m), called the

Float; whence it is laded into lesser troughs or moulds, each of which contains about three hundred of Metal.'

Additionally, from the 18th Century, there is a description of the furnace at Old Blowing House in St Austell - one of the last to operate - provided by Charles Hatchett, who visited in 1796 (Raistrick 1967 p25-6). The furnace, which was made from granite, stood 9 to 10 feet (2.75 to 3 m) high and had a shaft shaped like 'a double cone', i.e. with a fattened waist. There was a hatch or door in the side wall, about half way up the shaft, for the purpose of charging the furnace. An inclined flue 20 fathoms (36 m) long extended from the conical top of the shaft to a circular building wherein the escaped tin dust collected. A small sketch of the blast furnace was included in Hatchett's account.

A Cornish blast furnace of similar design is described in Karsten's 1832 publication *System der Metallurgie* (Mantell 1949 p125).

Hatchett is the first to record the use of blowing cylinders as a replacement for traditional bellows; these apparently being in use at St Austell New Blowing House.

In addition to these accounts, there is a detailed depiction of a blowing house showing elevations, plans and sections in an 18th Century print, based on sketches made by an anonymous German travelling in Cornwall (though the illustration is usually attributed to Raspe) (Earl 1991 p62-3). This shows a cone shaped shaft within a furnace, which except for the front portion, is constructed of regular blocks; some manner of door or plate appears to fill this opening. Two bellows worked by a waterwheel enter the shaft from the back of the furnace. A long narrow channel is cut into the ground at the front of the furnace. An inclined flue leads down from the top of the shaft, travels horizontally for some distance before appearing to rise vertically to a small building on a hill, openings in which would allow the smoke to escape. A refining basin, with a fire

underneath it to keep the tin molten, is shown. A small rectangle adjacent to the basin may be a sample mould.

Descriptions of furnaces in the 19th Century can be found in the Aikins' *Dictionary of Chemistry and Mineralogy* (Aikin & Aikin 1807), an article in *The Mining Journal (Vol 130)* for 12 December 1835 (Brooke 1998 p69), and Dr Ure's *Dictionary of Arts, Manufactures and Mines* (Ure 1853 p855, 1875 p1005-6). These indicate that the basic design of these later blowing houses is not markedly different from their 18th century counterparts, although some refinements were made, such as changes to the dust collection system, the design and construction of the float, and the method of draught delivery.

This is illustrated by the description included the work of Leifchild, though the time of the blowing houses was all but over when he published his account of Cornish mining in 1855 (p210). 'The blowing house furnaces are about 6 feet (1.8m) high from the concave hearth to the throat, or commencement, of the long narrow chimney, which, after proceeding for some distance in an oblique direction, contains a metallic chamber, in which the metallic dust carried off by the blast is deposited. The blast is introduced either from large bellows or cylinders. No substance is added to the ore and charcoal, unless it be the residuary matter of a previous smelting. The proportion of charcoal consumed is about one ton and six-tenths for every ton of tin produced. The melted tin runs off from the furnace into an open basin, whence it runs into a large vessel, where it is allowed to settle. The scoriae are skimmed off; and subsequent operations consist of refining, by allowing the mass of the metal to rest, then submitting the upper and pure portion to the refining basin, and remelting the lower part'.

The Blowing Process

In addition to the descriptions of the furnaces in use in the 18th and 19th Centuries, most accounts give some details of the blowing process; these are summarized in Table 1.7. From these, it is possible to gain a broad idea of working practice. Similarities with the accounts of blowing houses by earlier writers can be seen, and the later works have been of use in helping to clarify this earlier material.

Furnaces were pre-heated, probably for four or five hours before the ore was added (Brooke 1998 p347). Charcoal is the only fuel mentioned; this was placed in the furnace at regular intervals, interspersed with layers of ore. No fluxes were added, but a quantity of slag from a previous smelt may have been included in the charge. It is difficult to determine exactly how much ore and charcoal were needed to produce a certain mass of metal; in part because measures of variable size are used (the value of the hundredweight falls between certain limits; the mass equating to a shovelful is harder to determine), and in part because quantities of charcoal are given by volume without taking into account that the density of charcoal will vary depending upon tree species and how the charcoal was produced (Overman 1852 p347). These problems have been considered by Earl (1985, 1991 p56). Factors affecting the amount of ore and charcoal used may include how well the furnace was operating, the size and design of the furnace, the quality of the ore and what type of charcoal was being used.

The furnace appears to have operated for 12 hours (a period of time referred to as a tide). Molten metal flowed from the base of the furnace and collected in a float or basin in front of the shaft. A small quantity of slag flowed out with the metal, upon which it floated. This slag was removed, and may have been retuned to the furnace during smelting. Some accounts suggest that the metal was ladled directly from the float into

Table 1.7: Details of 18th and 19th Century Blowing Process as given in Contemporary Accounts

Date	1725	1778	1796	1807	1835	1855
Source	Kalmeter	Pryce	Hatchett	Aikin	Mining Journal	Leifchild
Fuel	24 packs of charcoal per day (2.52m^3)	18 to 24 sixty gallon packs of charcoal (1.89 to 2.52m^3)	Approx 2:1 charcoal to ore by volume	2 or 3 half bushels of charcoal at regular intervals (0.035m^3 or 0.05m^3)	Charcoal used	1 ton and six-tenths of charcoal for every ton of tin produced
Ore	800 lbs per day (364 kg)		No more than 2 hundredweight (104 kg) smelted at a time	3 or 4 shovelfuls of ore (c.12 to 30 kg - estimate from Earl 1985)		
Metallic tin output		8 to 12 hundred weight (436-654 kg) in a tide of 12 hours	65 to 75% of mass of ore feed			
Furnace operation	Preheating of furnace for 4 or 5 hours before charging	Charging of furnace with layers of charcoal and ore		Preheating of furnace before charging Charging of furnace at short intervals with ore and charcoal	Charging of furnace with ore and charcoal at short but regular intervals	
Slag Recycling				Small quantity of slag flowing out of furnace with metal thrown back into the furnace		'Residuary matter' of a previous smelting could be added to charge

Tapping and metal collection	Tap hole permanently open Discharges to trough or mould at front of base of furnace	Text implies tap hole permanently open Collection in float Ladled out of float into moulds with a capacity of three hundred (163 kg)	Tin ladled out of float Refined in iron basin by 'boiling' with wood Metal not remelted	Tin flows continuously into pit below furnace Tin ladled out of full pit into c.1m iron boiler with fire beneath Tin allowed to cool slightly to avoid metal becoming brittle when put in mould Ladled into moulds with a capacity of two to three hundredweight (109 -163 kg)	Molten metal collects in bottom of furnace Tapped into float or kettle Slag separated by ebullition Metal cast into blocks	Melted tin runs out of furnace into open basin Runs into large vessel where it settles Scoriae skimmed off Metal refined: upper pure portion put into refining basin; lower part remelted

moulds; others (e.g. Hatchett in Rasistrick 1967 p26) indicate that refining took place. The removal of impurities such as trapped slag from the metal could be effected by ebullition, whereby wet charcoal or wood was placed into the molten tin causing it to bubble vigorously; slag was then removed from the surface. If necessary the tin metal was then allowed to settle, which allowed the purer tin to rise to the surface of the basin, from whence it could be ladled off. The less pure metal, usually contaminated with iron, was denser and sank to the bottom of the refining basin. This would be remelted. Pryce (1778 p136) states that in a twelve hour period a blowing house could produce 8 to 12 hundredweight of tin (436-654 kg), which was cast into blocks of approximately 3 hundredweights (163 kg) each.

The Reverberatory Furnace

At the beginning of the 18th Century the nature of tin smelting furnaces changed. This was precipitated by the need to increase metal output and reduce costs by finding an alternative to charcoal fuel. Reverberatory furnaces had been used for copper smelting for some time, and attempts were made to adapt this type of furnace to the smelting of tin from the late 17th Century. Treloweth blowing house (SW537354) was reputedly the site of the first furnace, built by John Joachim Beccher before 1682 (Hawkins 1832), while Celia Fiennes (1695) makes reference to trials carried out at Polgooth (SW993502). It was in 1702, however, that Robert Lydall took out a patent for smelting tin in reverberatory furnaces, followed by a subsequent patent in 1705 stating that culm or sea coal would be used, and went into partnership with Francis Moult and Richard Hoare to establish furnaces first at Newham in 1703 (SW829441), and then at Angarrack (SW583382) in 1704 (Henderson 1912; Barton 1971 p86; Higgans 1979; Smith 1996; Brooke 1998 p74).

The transition to the new smelting method initially met with some resistance, with competitors challenging the Newham partners in the courts over the quality of the tin being produced, but, equally, interested parties were quick to see the advantages of the method: reverberatory furnaces were established at Treyew (SW8144) even before the expiration of the patent that granted a monopoly to Lydall and partners, and challenges were made to it (Barton 1971 p85-87, p92-9). Following the patent's expiry the technology was very quickly adopted.

Where the blowing houses had always been relatively small-scale operations, the smelting works represented big industry. Multiple furnaces were the norm: for example, Chyandour had 4 (Barton 1968 p141), Perran Melting House had up to 6 (Sherborne Mercury 4/1/1802) and Calenick had 10 or more (Maton 1797); although Kalmeter (Brooke 1998 p70) noted that furnaces stood idle much of the time, full capacity only being required in the run up to coinage.

Reverberatory Furnace Design

Reverberatory furnaces consisted of a wide concave hearth-bed, partially separated from an adjacent fireplace by a low partition wall (called the fire bridge), with a low arched roof (the fire arch) over all. Thus the main difference in the design of reverberatory and shaft furnaces was the separation of ore and fuel. Long-flame fuels such as pit coal replaced charcoal, and heat from the fuel was reflected onto the bed by the curved roof. The ore bed sloped gently towards the tap-hole, which was sealed during smelting. At the front of the furnace was a working or raking door, which permitted the ore bed to be raked over; at the side was a charging door to allow ore to be introduced; at the rear was a door to allow access to the fireplace. Figure 1.16 shows the basic design of the reverberatory furnace. A chimney was located at the end of the

furnace furthest from the fireplace. Multiple furnaces might be served by a single stack, though many did have separate stacks.

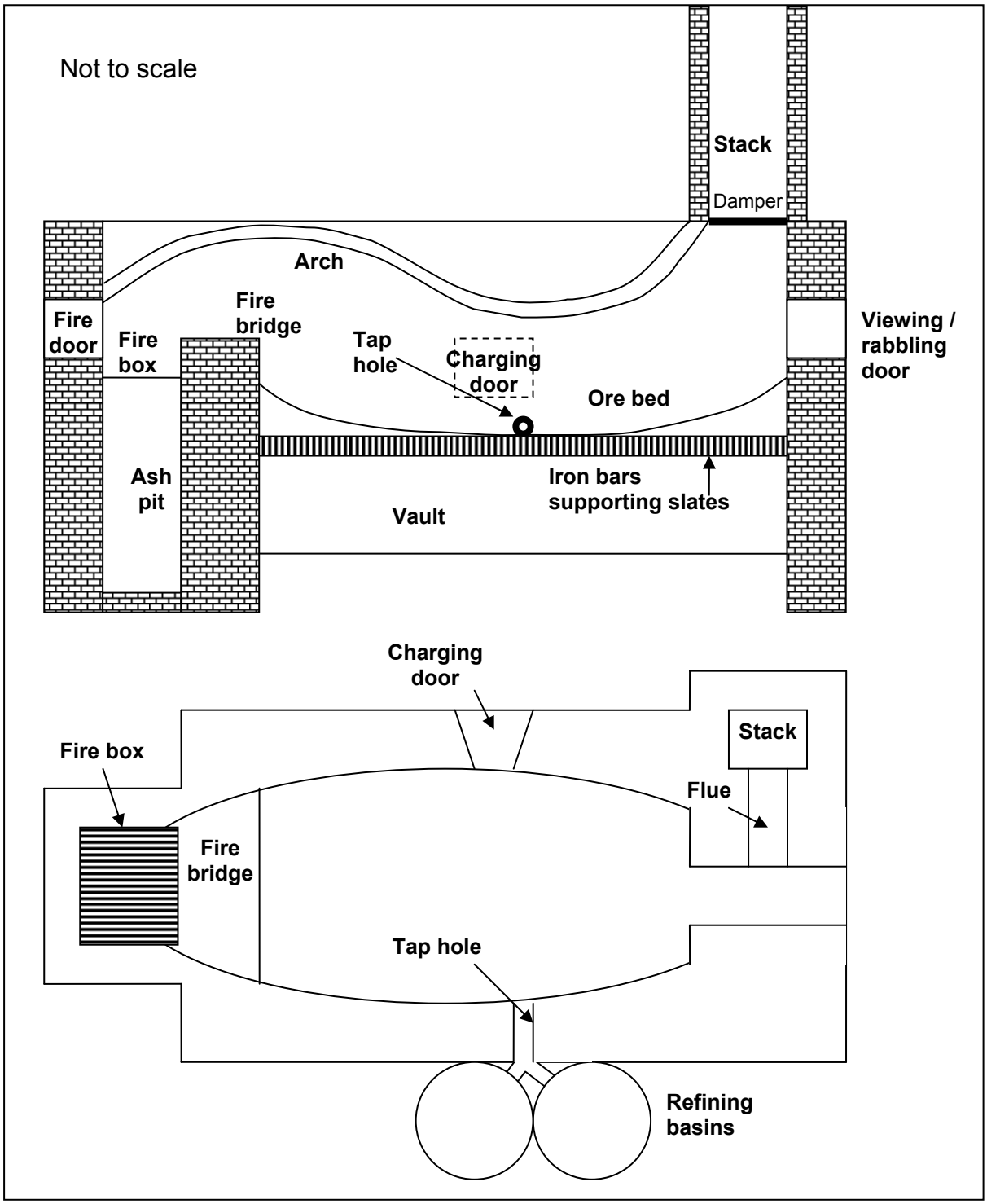


Figure 1.16: General plan and section of an 18th Century Reverberatory Furnace (after Leifchild 1855 p212 and Barton 1968 p135)

The early furnaces appear to have been constructed of brick reinforced with granite slabs, with a hearth-bed of brick and clay; later they were built wholly out of firebrick. Reverberatory furnaces had a capacity substantially greater than shaft furnaces, and capacity increased over the space of about 3 centuries (see Table 1.8).

Several contemporary descriptions of reverberatory furnaces exist. Kalmeter (Brooke 1998 p70, p344) describes them as being '12 feet long (3.6m), 6 feet wide (1.8m) and 4 feet high (1.2m) from the ground. The walls, which were built of bricks laid lengthwise and protected or covered outside by granite blocks, were two feet thick, with strong iron bars laid lengthwise and crosswise around the walls to hold the furnace together, so that with this strong reinforcement it would not burst with the great heat. The bottom of the furnace consisted of a base of large slates, which rested on strong iron bars, and had a covering of clay, on which bricks were laid on end with the gaps filled with more clay mixed with broken brick. In one end of the furnace is the fireplace, which is of the same width as the furnace and two feet long between the outer walls. The wall, in which there is a door for throwing in the coal, can be called the cross wall, as it goes across the width of the furnace from one wall to the other. The coal lies on the iron bars laid crosswise, and through these the ashes fall and the draught goes up through an opening which is below the fireplace... On the other end of the furnace is the chimney, which does not stand on the same wall as the furnace but on a wall with foundations of its own, having another chimney or pipe which goes up from the chimney of the furnace and into the other, and leads the smoke into it. This is so that one does not need to demolish the bottom of the chimney every time the furnace, and what they call the flue, have to be repaired. The cross wall already mentioned extends below the iron bars on which the bottom of the furnace rests, though not down to ground level, and at the bottom part of this wall there is an oval hole to help the draught to become even

stronger, and this [is done] by means of an opening, like the one under the fireplace, which goes the length of the furnace along the ground under its bottom, from the end where the chimney is to in under the fireplace, and is not over a foot wide. The cross wall is 1½ feet (46 cm) thick, built of clay and broken bricks mixed, but does not go up to the roof of the furnace, as there is a distance or space of 20 inches (51 cm) between the top of the wall and the roof of the cupola. The furnace is not all the same height inside, for near the cross wall its roof rises in a so-called cupola or vault to a height of 2½ feet (76 cm), and then slopes gently down, by which the roof slopes until it is no more than a foot high (30 cm) at the pipe leading to the chimney, in order the make the flames play down on the ore. Neither is it equally broad or wide inside, even though it looks four-square from the outside, but widens a little towards the cross wall and narrows again, until at the chimney it is not over a foot wide (30 cm) and of the same width as the door on that end of the furnace, so that one can heap up and spread out the ore with a rake, as well as draw out the slag which falls when tin slags are re-melted, for when the ore is smelted the slag runs off with the metal. In the middle of the side or wall of the furnace is another door, which, like the other, is closed with an iron catch during smelting, through which the ore is thrown in and spread out on the bottom, four or five inches deep (10–13 cm) and over a length of six feet (1.8m), starting just close to the spot where the cupola begins. Close to this door and opposite the end where the chimney is, is the hole through which the molten metal runs, and for this purpose the furnace is built in such a way that the bottom slopes a little towards this hole.'

Pryce (1778 p282-3) begins his description of the reverberatory furnace by stating that it 'differs little from that made use of for smelting Copper, only it is not quite so deep' (The dimensions of copper furnaces are given as follows: External measurements: 18 feet long (5.5m), 12½ feet broad (3.6m), 9 ½ feet high (2.9m); Internal measurements:

length of bed 7 feet 10 inches (2.4m), breadth 4 feet 8 inches (1.4m), average height 2 feet (0.6m); fireplace 2 feet 8 inches long (0.8m), 2 feet wide (0.6m).)

Pryce goes on to describe the smelting process, giving further details of furnace design:-'The charge for one of these furnaces is from 5 to 6 cwt (255-305 kg) of black tin, well mixed with a tenth or a twelfth its weight of culm. This furnace is charged through a hole in the side (directly opposite the taphole), through which it is thrown into the furnace with a shovel, and levelled over the bottom with an iron rake or paddle, from the mouth. This done, the apertures are immediately closed and the fire raised to a very great strength, in which state it is left between four or five hours, when the door is taken off and the whole charge is well stirred together. The foreman of the works at this time examines the state of the metal and if he thinks it convenient orders an additional quantity of culm, at his discretion, to be put into the furnace, after which it is closed again and left in this condition, the fire all the time being kept fully up, till the end of about six hours from its receiving the charge, at which time it is again examined by the foreman, and if he finds it proper, is then tapped and the metal let out into a fixed basin made of clay, with a capacity to hold something more than the metal in the charge, as in some sorts of tin, the scoria being vitrified to a considerable degree, part of it will therefore flow out with the metal; but this is not commonly the case in any large quantity. The scoria remains in the bottom of the furnace and is raked down at the mouth and falls into a small pit under it made for the purpose and has generally adhesion enough to form into a cake'.

The similarity of tin reverberatory furnaces to those used for copper smelting was noted again by an anonymous writer in 1790 (Swete 1971).

Hatchett, describing his visit to Calenick in 1796 (Raistrick 1967 p29-30), where there were then 10 furnaces, also says that these were smaller than copper furnaces, being 2m high, with hearths 23cm deep, 2.1m long and 1.1m wide.

Calenick was also visited by Maton (1797), in 1794, who gave the furnace dimensions as 6 feet high (1.8m), 6 feet long and 3 feet broad (0.9m). This works is mentioned again by Leifchild (1855 p211), who says 'it comprises ten or twelve furnaces, each six feet high (1.8m), and nearly twelve feet in length (3.6m)'; these took a charge of 12 to 16 cwt (610-815 kg) of a mixture of 1 part culm to 8 parts ore.

Leifchild (p212) also presents a plan and section - showing the concave hearth, the chimney, charging and raking doors, and the collecting basins for the molten tin - of the reverberatory furnace at St Austell, which had a larger capacity: 15 to 24 cwt (765-1222 kg).

Furnaces depicted by Dufrénoy (1837), who wrote on Cornish reverberatory practice around 1834, are not dissimilar in size and design from those depicted by Hatchett.

At the beginning of the 20th Century, Thibault (1908 p187-8) notes that the details of the various reverberatory furnaces in use in Cornwall differ, but bed dimensions were in the range of 16-18 feet long (4.9-5.5m) and 8-12 feet wide (2.4-3.6m), the fire bridge being 6 feet long (1.8m) by 2 feet wide (0.6m); the depth, from the fire arch to the bottom, was c. 3 feet (0.9m), and below the fire bridge 15 inches (0.4m).

The construction of a typical furnace is described thus: 'The bed is carried upon transverse iron bars, upon which rest slabs of slate, or fireclay tiles; these are covered by a bed of clay from 6 inches to 9 inches deep, and upon this rests the bed proper, which consists of good sound firebrick laid on end, close together, and well grouted

in… The bed is made shallow, with a ‘dish’ of about 6 inches and slopes from all sides to the taphole. There are two doors in the furnace: one opposite the taphole, and which is used for charging, and another the working door [or front viewing door] which is situated at the flue end… The fire door is located opposite the working door. To be strictly correct it is not a door at all, but only an opening in the firebox… Each furnace is provided with its own stack, of a height of about 50 feet (15m)… The brickwork of the furnaces is held together by iron plates, buck-staves and tie bars. Under the bottom of the furnace a brick float is laid, which has a slope from side to side towards an iron pan. By this means the molten tin that constantly percolates through the hearth of the furnace collects in the pan, from which it may be removed when convenient. In front of the taphole a cast iron float is placed…’

These later furnaces had large capacities, varying from 2700 lb (1227 kg) up to 3 tons (2722 kg). Thibault reports that the Penzance works smelted four 2 ton (1814 kg) charges in 24 hours.

A summary of the features of reverberatory furnaces is presented in Table 1.8.

Table 1.8: A Comparison of 18th Reverberatory Furnaces from Contemporary Descriptions

Date	1725	1778	1794	1796	1855	1883	1908
Source	Kalmeter's Diary (Brooke 1998 p70, p217, p344)	Pryce (1778 p282-3)	Description of Calenick in Maton 1797 (Barton 1968 p132)	Hatchett's Diary (Raistrick 1967 p29-30)	Leifchild (1855 p211-2)	Description of Chyandour in The Cornishman 1/3/1883	Thibault (1908 p187-8)
Source type	Written account	Written account + plan and section	Written account	Written account	Written account + plan and section	Written account	Written account
Length	Ext 12 ft (3.6m)	Ext 18 ft (5.5m); Int length of bed 7 ft 10 in (2.4m), fireplace 2 ft 8 in (0.8m)	6 ft (1.8m)	Hearth length 2.1m	Calenick: 12 ft (3.6m)	-	16-18 ft (4.9-5.5m)
Width	Ext 6 ft (1.8m)	Ext 12ft (3.6m); Int width of bed 4 ft 8 in (1.4m), fireplace 2 ft (0.6m)	3 ft (0.9m)	Hearth width 1.1m	-	-	8-12 ft (2.4-3.6m)
Height	Ext 4 ft (1.2m)	Ext 9.5 ft (2.9m), Int average 2 ft (0.6m)	6 ft (1.8m)	Overall height 2m Hearth height 23 cm	Calenick: 6 ft (1.8m)	-	-

Furnace Capacity		5-6 cwt (255 – 305 kg)			Calenick: 12 to 16 cwt (610-815 kg) St Austell: 15 to 24 cwt (765-1222 kg)	28 cwt (1425 kg)	2700 lb - 3 tons (1227 - 2722 kg)
Material of construction – furnace body	Brick with outer shell of granite blocks; total wall thickness 60cm.						Brick held together with iron plates and tie bars.
Material of construction – ore hearth	Base of large slates covered with clay, resting on iron bars. Overlaid with bricks, gaps sealed with clay / brick mix.						Base of slate or fireclay tiles covered with 6-9 in (15-23 cm) of clay resting on iron bars. Overlaid with firebrick, grouted in.
Method of Charging	Through door in the middle of the side wall	Through side door					Through side door
Tap hole	Located close to charging door, at end away from the chimney.	Opposite charging door; sealed during smelting					Opposite charging door, sealed during smelting

Float		A fixed basin made of clay, with sufficient capacity to collect all the metal produced + small amount of slag			'Basin of reception' connected to hearth by a channel; melted tin collects and is allowed to rest before being transferred to moulds		Brick float under furnace, sloping towards iron pan which collects tin percolating through the hearth. Cast iron float placed in front of taphole.
Chimney	Trereife: pairs of furnaces share 70 ft (21m) stack			12m high; 46 cm square inside		Single shared stack	Individual stacks, c.50 ft (15m)

The Reverberatory Smelting Process

As for the process of smelting in reverberatory furnaces, several accounts are available. Most clearly illustrate the differences between reverberatory and blast furnace practice.

One of the main differences is that furnaces were heated using coal rather than charcoal, approximately 1 ton being consumed for every 1 ton of black tin smelted (Barton 1968 p141), and whereas in the blast furnace charcoal acted both as fuel and reducing agent, the separation of fuel and ore in the reverberatory furnace meant that it became necessary to mix the ore with a reducing agent. Culm coal was suitable for this purpose, but later smelters also used powdered anthracite. The reducing agent was sometimes incorrectly referred to as flux by the smelters; reports from the mid-19th Century indicate that true fluxes were added to the charge on occasion (see p177).

The furnace was sealed, the taphole only being opened periodically, and sometimes just once, at the end of the smelting process, when the molten tin was allowed to flow into the float. Further refining of the metal was then necessary.

Referring to the use of coal as fuel, Kalmeter (Brooke 1998 p344) states that 500 lbs (227 kg) of black tin required 4 Winchesters (c.14.5 litres) of coal. After noting that '…during the smelting they mix the better with the poorer ore, so that the one may help the other and make all the tin alike', which suggests that the practice of carefully grading the black tin before it was smelted had been discontinued (cf. blowing house practice, see p127), his description of smelting continues as follows: 'For each smelting 500 lbs (227 kg) of ore are thrown into the furnace, which is let out every three to five hours, all according to whether the ore is hard or tough. But with the re-smelting of slags they let the metal out more often, mostly every quarter of an hour, making ingots of about 50 lbs (23 kg) weight, and all from a small cart load of slag, which they put in

all at once. To help the ore to melt it is mixed… with 1/5th powdered culm, so that for 500 lbs of ore they take between 70 and 90 lbs (32-41 kg) of culm, which are mixed together by putting a layer of one upon a layer of the other, while the rest which remains, or about a fifth part, is thrown in through the door by the chimney as needed. But with slag smelting the culm is thrown in separately afterwards, through the same door.

'So long as they hear working, simmering and boiling in the furnace during smelting, it is a sign that not everything is smelted yet, but when it stops they have to run the metal out, and when smelting slag they let the metal out as soon as it becomes molten. When the ore is smelted no slag runs out, as noted, until the molten metal runs out, so they skim off the slag and smelt it again when they have the time, in the manner mentioned. If they have some little tin or pieces from previous smeltings which do not make up sufficient weight for a block or piece of about 300 lbs (136 kg) they lay them in the float, to be melted by the molten metal that runs out. None of the slag produced by this second smelting runs out, but is raked out through the door by the chimney; it is not smelted any more but is stamped small and put on one side to be brought in again with other smaller or larger pieces.'

The work of Pryce (1778) quoted above (see p168) differs only in minor detail from that of Kalmeter.

Hitchens & Drew (1824 p618-9) state briefly that tin ore is 'melted in a reverberatory furnace with pit coals, and about one eighth of its weight in culm. This however gives the metal a degree of brittleness which the charcoal does not beget; and, in conjunction with the mundic still remaining, tends to lessen its value in the market. Common tin

taken from the mines, procures, after having passed through the burning house, about 13 pounds (5.9kg) of metal for twenty pounds (9.1kg) of ore.'

Leifchild's (1855 p211-2) 19th Century account of the process begins by noting that pit coal is used as fuel. It continues thus: 'The prepared ore is mixed with culm, and a flux added. These substances being blended, and a little water added to the mixture to facilitate the operation of charging the furnace, then from twelve to sixteen cwt (610-815 kg) of this mixture from the ordinary charge, or in the smelting furnaces of St Austell from 15 to 24 cwt (765-1222 kg). The charge is spread upon the concave hearth of the furnace, and then the apertures by which it is inserted are closed and luted. The furnace, being gradually heated, is kept hot for six or eight hours, by which time the reduction of the ore is completed. One of the apertures is then opened, and the melted mass stirred up to complete the separation of the tin from the scoriae, which are then drawn out by means of an iron rake. These scoriae consist chiefly of masses of refuse matter, though some pieces are reserved for further processes. The refuse being removed, a channel is opened, by which the melted tin flows from the hearth into a large vessel, called the basin of reception, where it rests for some time, that remaining impurities may separate by specific gravity. When settled, the tin is ladled into moulds, so as to form it into large blocks or ingots.' The blocks are said to 'weigh from two and three-fourth cwts (140 kg) to three and three-fourth cwt (190 kg) each'.

Thibault (1908 p188-9) gives details of early 20th Century practice: 'The ore charges are mixed with from 15 to 20% of culm, incorrectly termed by the smelters 'flux', together with small and variable quantities of slaked lime, according to the composition of the ore to be smelted. Sometimes fluorspar is used. Foul slags and drosses from previous operations are also mixed with the ore…

'…A strong fire is made up, and the prepared charges shovelled in, and by means of a rabble worked from the front door is spread out evenly over the hearth. This being completed, the doors are closed and luted, and the fire urged on. In from one to three hours, the charge is pretty well melted, at which period it is examined and rabbled, this being repeated from time to time. The temperature of the furnace is maintained at its maximum throughout these operations. Five to seven hours is the time generally occupied for complete reduction of the charge. When such is the condition of things, the molten slag is drawn out, through the front door, by means of rabbles… [Erroneous repeated line in text] …allowed to stand for some hours and if any dross rises it is thickened by the addition of some culm. The slag drawn from the furnace in this way is termed 'pulled slag'. The other portion of the slag remains on the surface of the metallic tin in a molten state, and is tapped out with the tin, from which it separates in the float, and is removed as soon as it has solidified.

'This is known as glass, and is resmelted. The top layer of 'pulled slag' which constitutes about $^{2}/_{3}$ of the whole, is considered clean enough to be discarded.

'During the smelting of a charge the taphole is kept closed by means of an iron bar about $1^{1}/_{8}$ inch diameter, termed the 'clay stopper bar', which is clayed into its place. When as much slag as possible has been drawn out through the front door, this bar is drawn and the tin and 'glass' flow into the float…

'After the 'glass' in the float has been removed, the tin is allowed to stand for some hours, and if any dross rises it is skimmed off and set aside for resmelting with other ore charges. The tin is then ladled out into moulds of about 100 lb (45 kg) capacity, and the ingots are ready for the refining process.

'The consumption of fuel is approximately 100% of the ore charged.'

The equivalent section in Louis (1911 p95), who Thibault paraphrases, is as follows: 'In from 5 to 7 hours the operation is usually completed, the temperature being about the melting point of cast iron. The mass is again well rabbled through and allowed to settle, so that the metal may separate as completely as possible from the slag. The slag is then drawn out through the working-door, by means of rakes or rabbles, and if it appears too thin it is thickened by a few shovelfuls of culm; it is known as 'pulled slag'. The top layer of slag that is first drawn off (about two-thirds of the whole) is generally considered clean and not to be worth further treatment. The next lot contains a good deal of tin in the form of shot or prill, and is sent to the stamps to be crushed and washed, old furnace beds or other residues being treated in the same way. The remainder of the slag requires to be re-smelted together with the prill obtained by the treatment of the previous lot. Not all the slag is obtained in the form of pulled slag; a certain amount remains on the metal in a molten condition and runs out with it into the float when the furnace is tapped; it rises to the top and forms a layer on the tin in the float, and is removed as soon as it has set. This slag is known as 'glass' and has also to be re-smelted. The tap-hole is always closed during the smelting operation by means of an iron bar… After as much slag as is possible has been drawn out, this bar is pulled out and the tin runs into the float together with a certain amount of glass.'

It is clear from the descriptions of reverberatory smelting that the tin being produced usually required refining.

Kalmeter (Brooke 1998 p347) described the process thus: 'When the molten metal has stood a while in the float it is ladled with iron scoops into moulds, which are made of granite… holding about 300 lbs (136 kg) weight, for that is the size of the blocks, as they call them, or ingots. The molten metal is stirred up in these moulds, or rather it is

lifted up and poured from scoops so as to release all its dross and impurities and to become completely pure and clear, which impurities are quickly skimmed off with wooden knives and are then smelted again. This is done so that the tin may become fine enough, and subjected to no tare or deduction at the coinage. When it has become a little cooler… they lay a brass plate on top of the metal, on which is the mark used by the smelting works, leaving its impression on the block.

'Those who have tin of several kinds, of which one or other is not as good as it should be, melt six or seven blocks or pieces in an iron kettle in order that they may be well mixed and become all of the same grade.'

Pryce's (1778 p284) account reveals a somewhat more lengthy process. He states that after being allowed to settle in the float for some time, the tin was ladled out into moulds, thereby being formed into blocks of less than a hundredweight (51 kg). Twenty or more of these blocks were then placed back in the furnace and re-melted, the molten tin flowing out through an open taphole into a refining float, larger than the float used during smelting. Here it was 'frequently stirred and tossed by a ladleful at a time held arm high, letting it fall in a stream into the mass of Metal, when the scum which arises is taken off'. The tin having been allowed to cool somewhat, iron scoops were used to transfer it to moulds holding approximately 3 hundredweight (c.153 kg), and were stamped when they had solidified sufficiently to hold the impression.

In the bottom of the furnace some metal would be left: 'the drossy part with which the Tin was contaminated, and which not melting with the slow fire made use of, holds with it a considerable portion of good Tin'. The temperature in the refining basin would be increased, so as to liquefy this material and allow it to flow into the float 'where the tin subsiding, and the dross rising to the top, the latter, soon cooling, is taken off and set

by, and the Tin laded into small slabs as at first to be again refined… The Tin that remains in and about the scoria and dross of the last tappings, &c. is recovered by repeated smeltings, until at last being almost entirely drained of that Metal, they become what the workmen generally call Hard-heads, consisting of such heterogeneous Metals as were included in the first mixture, and esteemed of no further value.'

Leifchild (1855 p211) says of refining only 'Refining consists of several processes preliminary to the actual refining, which is effected by plunging billets of green wood into the melted tin in the refining basin'.

Thibault (1908 p208-10) is more informative: '…the impure tin is heated on the inclined bed of a furnace at a temperature very little above its melting point. The comparatively pure tin, which melts or liquates out, flows down the inclined bed and is received in a large float, in which it is left in a molten state for some time. The more infusible portion of the impure tin remains on the bed of the furnace… and consists essentially of an alloy of tin and iron, which is known as hardhead. Frequently it contains sulphur, arsenic, copper and other impurities. …These infusible residues are sent back to the ore or slag smelting charges.'

Some impurities cannot be removed through liquation and the tin is either 'tossed' (i.e. repeatedly poured from a height using a ladle), or the method of 'boiling' or ebullition of the tin is employed, generating steam and gases that cause the tin to erupt violently so that 'a large surface area of the molten tin is exposed to the oxidizing action of the atmosphere, and the more easily oxidizable metals are converted to oxides, which having a lower specific gravity than the metal itself, float upon its surface. These are skimmed off from time to time...'

After boiling or tossing, the tin was allowed to cool for several hours before being ladled out into moulds, both to allow impurities denser than the tin to separate out and sink, and because the quality of the casting depended upon the temperature of the tin.

1.4.7.5: The Distribution of 18th and 19th Century Smelting Sites

Having examined the smelting process, the location and distribution of 18th and 19th Century smelting sites will be considered. Documentary sources give a relatively clear picture of the distribution and numbers of later blowing houses (see Catalogue of Smelting Sites).

In the main these were situated in Cornwall. Kalmeter noted that 13 were operational in 1724, six being idle (Brooke 1998 p78). Details of individual houses, including those associated with reverberatory smelters, have been presented by several researchers including Barton (1971 p80-2), Thomas (1974), Brooke (1998 p228) and Herring (2005).

In the 18th Century the majority of the blowing houses were concentrated in the western districts of Cornwall, but it was in the St Austell area that the blowing houses survived longest: the last closing in the 1860s (see p155).

Blowing houses in Devon were less common (Greeves 1996): in 1719 and 1730 only two are mentioned in Duchy of Cornwall records (DCO London/Inrolment Book 3, 1702-1715, 220; DCO London/Biographical Note of Duchy Officials p397), and one in 1751 (DCO London/Misc - papers prepared for binding by Richard Gray). Kalmeter also noted that in 1724 there were two houses in Devon (Brooke 1998 p78). A new but short-lived operation at Postbridge (SX6478), which descriptions suggest had both reverberatory and blast furnaces, produced tin in 1786 (DCO London/Dartmoor

Proceedings 1786, 14.9; 15.9; 14.10; 15.10; 13.11), but in 1791 it was stated that no smelting houses were operational (DCO London/Dartmore Applications for Grants from Messrs Carpenter, Fraser and Cole 1789-93, 20.11.1791). The last to operate was probably at Eylesbarrow (SX59196765), which closed in 1831: 'blowing house' is marked on a plan of Ellisborough Mine (WDRO/WW21) (Cook et al 1974).

Whereas the need for a water supply to power bellows had been the primary determining factor in locating the blowing houses, with the close proximity of mines to supply the ore a close second, smelting works that housed only reverberatory furnaces were freed from this requirement (although those that used water-powered stamps to crush their slags might still be situated close to streams). Almost from the outset, therefore, the choice of location for a reverberatory smelting works was close to a coinage town, or to a port in order to facilitate the delivery of ores and other materials for the operation of the furnaces (Barton 1968 p140).

Reverberatory smelting works were not numerous: Barton lists 35 major works (1967 p289) operating over 3 centuries (a few other smaller and more short-lived concerns existed). The majority were situated in Cornwall. In 1855 Leifchild (p210) stated that there were no more than 7 or 8 in operation.

Greeves (1996) has documented the reverberatory smelters of Devon, listing around a dozen for the entire period, most of which appear to have operated only for short spans, including the above mentioned Postbridge and Eylesbarrow works. The last smelting house to work in Devon appears to have been at Weir Quay (SX434651), which closed in 1890.

1.4.7.6: Archaeological Evidence for 18th and 19th Century Tin Smelting

Despite the prevalence of smelting in Cornwall in this period, structural remains of Cornish stand-alone blowing houses are very rare, and only occasional remnants of buildings of smelting works that had both types of furnaces survive; none have furnaces still extant. The vestiges of a building on the beach at Trevellas Porth, St Agnes (SW7261351923) probably represent the only remaining example of an 18th Century Cornish blowing house. Most smelting works were built on sites that have now been reused for other purposes. Parts of buildings or remains of walls that were part of Cornish reverberatory smelting works can be found at Calenick (SW820440), Mellanear in Hayle (SW559367), Newham (SW829441), Treloweth (SW537354), Trereife (Stable Hobba) (SW455294) and Treyew (c.SW8144) (see Catalogue of Smelting Sites).

In Devon, submerged ruins of the blowing house at Longstone (SX56076880) survive: a site that may have operated into the 18th Century (see p182). Partial structural remains of reverberatory smelting works can be found at Eylesbarrow (SX59196765), Impham Quay (SX43987055), Weir Quay (SX434651) and Whiddon (SX75457217).

Of these, Eylesbarrow is the only site with parts of the furnaces remaining. The granite-block walls of a rectangular building, measuring 18m by 6m (internal dimensions), are still visible, as are the remains of the two furnaces housed within. The blast furnace, situated in close proximity to a wheelpit at the western end of the building, consists of six substantial dressed granite blocks, which appear originally to have formed two pillars 1.5m apart which probably served as abutments to support a refractory lining (possibly of firebricks). From the northern wall of the structure a 22m long flue leads to

the ruins of a stack built on slightly higher ground (Cook et al 1974), now much decayed in comparison to the remains described by Burnard (1889) and Worth (plan dated 1922 in Worth 1940).

The reverberatory furnace, the remains of which cover a larger area, consists of several dressed granite blocks of various shapes; one is coated with slag. Firebricks, some broken, are to be found in this area. Slag also coated some of these broken bricks (Cook et al 1974).

Slag fragments have been recovered from Eylesbarrow and several other reverberatory smelters, including Carvedras, Charlestown, Trereife and Weir Quay, analyses of which are presented in Section 3.1. Other reverberatory smelting slags have been analysed by Tylecote (see p8).

1.4.8: 20th Century to Present Day

The 20th Century was a time of decline for the British tin industry. Although tin metal continued to be in high demand, particularly for use in tin-plating, most of the world's cassiterite was mined abroad, with South-east Asia, Bolivia and Nigeria dominating production. The amount of ore raised annually from Cornwall's mines in the period up to the Second World War was a fraction of that produced in the last half of the 19th Century: in 1935 output was 2,041 tons (2,078,000 kg) (Eastham 1936), and only 5 mines (Geevor at St Just, South Crofty at Cambourne, East Pool, Wheal Reeth and Mount Wellington), plus a few alluvial streamworks, were still operating (Brooke 1998 p64). By the 1960s only two mines remained: Geevor, which closed in 1990, and South Crofty, which though it closed in 1999 later reopened as the value of tin on the world market once again made the mine economical to work.

In the first decades of the 20th Century the tin smelting companies with interests in Britain underwent a series of amalgamations and take-overs and most of the approximately half dozen works that were operational in Cornwall around that time were closed. Amongst the casualties were the Mellanear works in Hayle, closed in 1905, the Chyandour works at Penzance, closed in 1912, and the Penpoll Smelter, closed in 1921 (Barton 1967 p289).

The last Cornish smelter was Seleggan, in Redruth, which having opened in 1887, used large reverberatory furnaces to process mainly imported tin ore. Two new 5 ton reverberatories, designed to be fired by burners on the side of the furnace above the hearth rather than having the fuel in a grated firebox, were installed at Seleggan in the 1920s: one was fuelled with oil; the second used pulverized coal, and proved the more economical of the two, as pulverized coal burned at a constant rate that could be

automatically regulated. Other refinements to the basic furnace design that were introduced at this time included a new condensing system to reduce amounts of tin lost as fume from the stacks. Subsequently a new 10 ton furnace was installed. Seleggan closed in 1931 (Barton 1968 p142; Earl 1991 p75).

Despite the closure of the Cornish smelters, the British tin industry was not completely moribund. New smelting works were opened, and for the first time were located outside of the southwest peninsula: Capper Pass & Son Ltd had works at Bedminster in Bristol, and at North Ferriby near Hull, while Williams Harvey & Co was based in Merseyside, these portside locations being convenient for the import of ores.

These new works continued to use reverberatory smelters for the majority of production. However, Capper Pass also used blast furnaces. These had a uniformly rectangular cross-section, and were fitted with up to 14 tuyères. The blast was delivered from two sides: opposite pairs of tuyères were 1.8m apart, while adjacent tuyères were 0.7m apart.

Tin metal was smelted directly in blast furnaces until 1950, but thereafter, until 1990, this type of furnace was used only to process complex, low grade concentrates, which generated such a high volume of slag that it could not easily be managed in a reverberatory furnace. The product was a tin/lead alloy, from which the tin was subsequently separated by electro-refining (Wright 1966 p103-4; Smith 1996).

Tin smelting in Britain came to an end in the final decades of the 20th Century. Williams Harvey & Co's smelter in Bootle, Merseyside, closed in 1972 and was dismantled to make way for housing, while the last works - the Capper Pass smelter at

North Ferriby, Hull, which in its final decade was producing c.10,000 tonnes of metal per year (Tylecote 1980a) - closed in 1991 (Brooke 1998 p64).

In the 21st Century, the two largest producers of tin ore, and smelted tin, are China (est.150,000 tonnes ore in 2008) and Indonesia (100,000 tonnes ore) (USGS Mineral Commodity Summaries 2009); these are followed by Peru, Bolivia and Brazil.

An overview of modern smelting processes can be found in Wright (1982). Three basic methods are currently in use: smelting with blast furnaces; smelting with reverberatory furnaces (an adaptation of this – the rotary reverberatory furnace – has been used in Bolivia); or smelting with electric arc furnaces. The electric furnace is able to produce extremely high temperatures, giving very strong reducing conditions, by means of graphite electrodes carrying extremely high currents placed into the charge (Uys 1977; Strachan et al 1990).

Chapter 2

Experimental Methodology

2.1: Collection of Samples

Artefacts relating to tin smelting, from sites in both Devon and Cornwall, were assembled, covering a range of dates from the Bronze Age to the Early Modern period. The samples, which included tin smelting slag, tin ore, fragments of furnace wall material and pieces of metallic tin, were obtained from a variety of sources, including Cornwall Archaeological Unit, museum collections, the collections of private individuals, and through fieldwork carried out by the author. See Figure 2.1 for a map showing the locations of the sites from which artefacts were collected. The source of the slags analysed in this work, the circumstances of their discovery (where known), and probable date, are shown in Table 2.1.

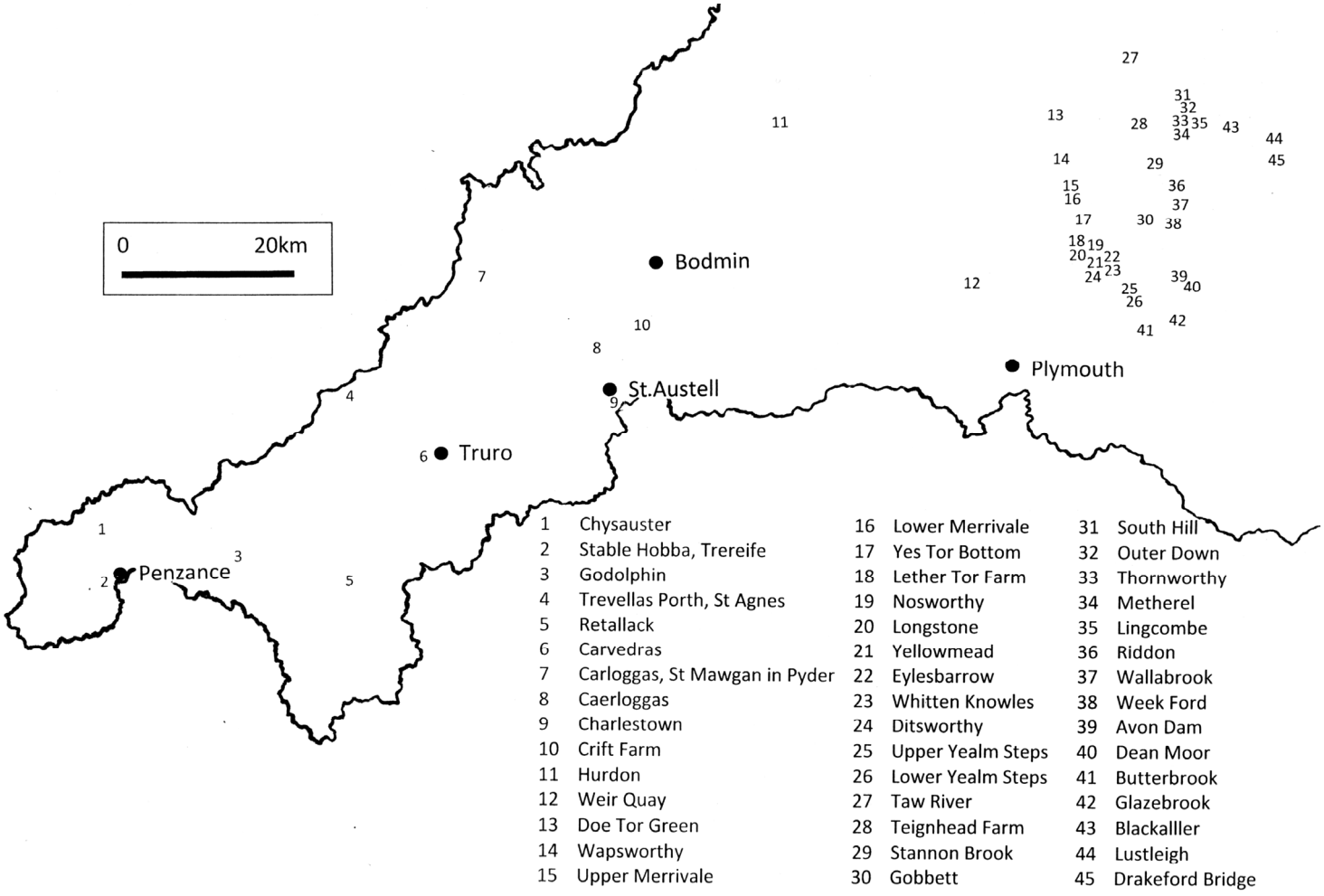


Figure 2.1: Map of Southwest England showing locations of sites

2.1.1: Tin Slag

A total of 88 pieces of slag covering 42 different sites have been selected from larger assemblages and prepared for analysis. Approximately half of these sites have not previously had any analysis carried out on the material from them. Samples from the other half of the sites are new pieces that have not previously been examined.

Of the sites that have yielded tin slag for this study, full archaeological excavation has only ever been carried out at five: one dedicated smelting site (Upper Merrivale (SX55197664)), 3 settlement sites (Crift Farm (SW067602), Metherel (SX66828402 and SX66978412) and Yes Tor Bottom (SX56697295)) and one ritual site (Caerloggas (SX01705659)). The remainder of the samples are finds from unstratified contexts. In most cases the slag was closely associated with identifiable structural remains and/or occurred in areas where documented smelting works are understood to have been situated, and thus the slag may be taken to be contemporary with the indicated site type. However, five samples were chance finds that cannot be linked to any known smelting work.

The necessity of relying upon unstratified surface finds is one of the limitations of this type of study. The assumption that a slag sample is contemporary with any remains with which it appears to be associated is not necessarily valid. Although the identification of the nature of the site may be incontrovertible, this does not exclude the possibility that slag found in the vicinity dates to an earlier or later period, or that the slag was produced elsewhere and brought in for re-treatment (see p421, p426). There is also likely to be an issue with multi-periodicity at sites where, as documentary sources attest, reverberatory furnaces and blowing houses were erected on the same site, whether contemporaneously or successively.

Another problem, on a site that operated for a prolonged period, is that unstratified slag samples do not allow any potential changes in the characteristics of the slag with time to be assessed. At best, the effects of changing ore quality or improvements in ore processing technique would show up as heterogeneity in the sample set.

It is also necessary to question whether the samples obtained as surface finds are representative of the bulk of the material on that site. The excavation at Upper Merrivale yielded some quite substantial blocks of slag, >100g, but the majority of the slag samples from other sites of similar age have masses of <10g. It may be, therefore, that transport of slag by plant and animal activity, ploughing, or erosive processes, has caused some sorting of material in buried dumps, smaller samples being more mobile in the soil than more massive specimens and thus more likely to be carried to the surface. Very small fragments of material, however, are liable to go unnoticed and are thus less likely to be collected.

While recognizing that a study based on data obtained from unstratified samples has inherent shortcomings, which will clearly result in some uncertainty in the findings, it remains the case that if unstratified samples are excluded from the study, there is simply insufficient material available to provide any meaningful temporal or geographical comparison of sites.

In addition to the samples listed in the table, finds of slag have been reported from a small number of other sites, but further examples of these were not obtained (see Appendix 2).

Table 2.1: Source of Tin Smelting Slags

Site	Sample	Source	Date and Type of Site
Avon Dam (SX67226553)	2/20	One of about 20 pieces of slag found by Mr Robert Smerdon about 1.8m away from the (probable) door of the mill.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Blackaller (SX73808370)	4/22	From a collection of six pieces of slag found amongst the gravel on the bank of the River Bovey on the opposite side of, and several metres downstream from, the house and garden, which is the assumed location of the mill. Collected by the author on 17/8/94. (A sample of slag from Blackaller found on 22/4/75was lodged in Plymouth City Museum by Dr Greeves, and this has been positively identified as tin slag. There is also iron slag in the vicinity of Blackaller, examples of which were given to the author by Dr Greeves.)	Blowing house. Documentary evidence states that a blowing house was in existence in 1527.
Butterbrook (SX64225920)	2/33 2/34	Loaned by Plymouth City Museum (Accession No 99), from thirteen pieces found by Dr Tom Greeves on 31/1/85 in the eroded riverbank west of the mill.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Caerloggas (SX01705659)	3/44 3/45	From a collection of seven pieces found within a Bronze Age ring banked enclosure, during excavations led by Miles (Miles 1975). Loaned by Royal Institution of Cornwall Museum, Truro. Both analyses of same fragment of slag.	Bronze Age ritual deposit. The slag was found in same context as a fragment of a dagger typologically dated to the Early Bronze Age.

Carvedras (SW82064494)	3/30	A single piece of slag found amid a quantity of clinker on the ground surface under the hedge at the base of the grass bank in front of the Carvedras Court housing complex, opposite Wellington Terrace, off George Street, Truro. Collected by the author on 10/7/03.	Smelting works with eight reverberatory furnaces. Documentary records indicate the works opened around 1720 and closed in 1898. Documentary records also indicate a blowing house operating on the site during some of this time (Barton 1971).
Charlestown Smelting House (SX03185219)	4/20	Sent by Mr Bryan Earl. Collected from the site of the reverberatory smelter, c.1993.	Smelting house with reverberatory furnaces, established 1834, closed 1884. There was no blowing house on this site: Charlestown blowing house was situated near Mount Charles, St Austell. (The Smelting House bought Bolivian and Australian ores in addition to Cornish ores).
Crift Farm (SW067602)	4/15 4/16 4/17 4/27	Samples excavated by Bradford University, being part of an estimated 1 tonne of slag at the site, mostly located in what appeared to be a dump against the southern-most corner of the building.	Probable pre-blowing house smelting. The slag was deposited around an early Mediaeval longhouse. Dating evidence suggests the site was in use some time between 10th and 14th Centuries.
Ditsworthy (SX5866)	3/01	One piece of slag, loaned by Torquay Natural History Museum (Museum reference: A 1787 Box 147), from a collection of five fragments found in July 1949. The circumstances of the find are not recorded.	Not known. The only tinner's building in the large area of Ditsworthy is at Mill Corner, which is not believed to be a blowing house.
Doe Tor Green (SX53338524)	2/12	From the collection of Dr Tom Greeves. Found in the vicinity of the tin mill on 14/3/93.	Blowing house. Documentary evidence for mill in 1594.
Drakeford Bridge (SX78788015)	2/19	From the collection of Dr Tom Greeves. Found in the bank of the River Bovey, Lower Smithy Park, above Drakeford Bridge on 7/2/99.	Not known. There is no documentary evidence for smelting at this location.

Eylesbarrow/ Ailsborough (SX59196765)	2/35 4/05 4/06	Loaned by Plymouth City Museum. A single piece of slag found by Dr Tom Greeves on 13/7/75, loose among debris of the reverberatory furnace at the smelting house. Upper and lower portions of a large piece of slag found on the track leading to the smelting house. From the collection of Dr Tom Greeves.	Smelting house with both a reverberatory furnace and a blowing house, in operation 1822-1831.
Glazebrook (SX66836031)	2/58	A single sample found by Mr Robert Smerdon in the tailrace of the mill.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Gobbett (SX64537280)	2/28	Slag obtained by Mr Robert Smerdon from a large pile of slag about 3m behind and above the blowing house. (Approximately twenty pieces of slag from the immediate vicinity of Gobbett blowing house were found by H French and are now lodged in Plymouth City Museum.)	Blowing house, probably 16th-17th Century.
Hurdon (SX210823)	2/01 4/26	Collected by the author on 20/8/94 from an area to the north of the earthwork remains of the blowing house.	Blowing house. Documentary evidence indicates a mill on this site in 1435.
Lether Tor Farm (SX56726981)	2/11	From the collection of Dr Tom Greeves. Sample found on 11/10/98 in soil above the entrance of a potato hole at the abandoned Lether Tor Farm on Leather Tor.	Possibly early. The find site is not associated with any known mill. (There is a documentary reference in 1511 to a tin stamping mill by Lader Torre, which may refer to one of the two mills at Nosworthy, and it is possible material may have been transported from there.)
Lingcombe (SX68838440)	3/19 3/20	From the collection of Dr Tom Greeves. Found on 13/4/03, lying in the footpath, which had been disturbed by a vehicle.	Blowing house, possibly Mediaeval/ Post-Mediaeval.

Longstone Mill A (SX56006876) Longstone Mill B (SX56076880)	2/06 2/07 4/24 2/47	From a collection of a few fragments found by the author on 19/8/94 on the shore of the Burrator Reservoir in the vicinity of the ruins of the mills at a time when the water level was low. (Longstone was visited by Greeves on 13/11/78, with four pieces of slag being collected from within 15 m of Mill A on its northeast side. This is lodged in Plymouth City Museum (Accession No 104).) From the collection of Dr Tom Greeves. One of twelve pieces from the north-west end of Mill B. (The remainder of the material from Longstone Mill B is lodged in Plymouth City Museum.)	Two blowing houses (or a corn mill (A) and a blowing house (B)) adjacent to each other. There is documentary evidence from 1623 and 1751 stating that a blowing house was in operation in the area, which may refer to one of the Longstone mills. A stone on site is inscribed 1740, but appears to be associated with the building believed to be the corn mill.
Lustleigh / Caseley (SX78778216)	2/50 2/51	Loaned by Plymouth City Museum (Accession No 113), from a collection of twelve pieces, which derived from an extensive spread of slag on the right bank of Wray Brook, gathered on 14/5/84 by Dr Tom Greeves.	Blowing house, probably operating c.1600, but possibly in operation as early as 1378.
Lower Merrivale (SX55277535)	4/04 4/28	Single sample found on footpath 10m above and to north of the mill. Collected by the author on 29/2/04. One of two pieces of slag found beneath organic material on the right hand side of the furnace structure. Collected by the author on 19/8/94.	Blowing house, pre-1700.
Upper Merrivale (SX55197664) (The blowing mill at Upper Merrivale was designated as		Samples provided by Dr Tom Greeves from approximately 12,000 pieces collected during the excavation of the mill complex by the Dartmoor Tinworking Research Group between 1991and 1996.	Blowing house. Probably 16/17th Century. Several phases of building were identified during excavation, indicating that the blowing house may have operated over a long period.

Mill A by the excavators; the adjacent stamping mill was Mill B.)		Find contexts as follows:	
	2/21	From the leat embankment under the south side of the revetment.	
	2/22	Contemporary with or earlier than construction of east wall of Mill A wheel pit area.	
	2/23	Mill A below stone flooring on south side of furnace; early smelting phase.	
	2/24	Openwork trench, at considerable depth in fill; possibly relates to phase soon after abandonment of openwork.	
	2/25	From tens of metres upstream from the mills; found in north end of upper trench.	Sample 2/25 may not derive from the blowing house. Slag from this area was associated with a prehistoric (or possibly Romano-British) pot sherd.
	2/26	Fill of stamps pit in Mill B.	
	2/27	Large slag piece from leat embankment.	
	2/31	Furnace area of Mill A.	
	2/32	Outside Mill B in ore dump; possibly later in chronology, marking end of or post dating last stamping phase but predating the last furnace phase.	
	2/52	Outside Mill B, under wall tumble; associated with Mediaeval jug.	
	2/53	Base of Mill B East wall i.e. predates Mill B.	
	2/54	Mill B outside; beneath wall.	
	2/55	From Mill B, against north side of in situ mortar stone; possibly relates to late stamping phase.	
	2/56	Mill A below wall; predates rebuild of Mill A.	
	2/57	Mill B, fill of stamping pit.	
	3/24	Mill A furnace area; associated with piece of pot dating to c.1600.	
	3/27	Under floor slab of Mill A on west side.	

Metherel (SX66828402 and SX66978412)	2/48 2/49	Slag was found in two of the prehistoric hut circles at Metherel during excavations by the Dartmoor Exploration Committee of the Devonshire Association in the 1930s (Worth 1935; 1937). Approximately twenty-five pieces of slag were found in Hut 3 (Museum reference: A3003 Box 31) and ten pieces in Hut 4 (Museum reference: A1997 Box 31). One piece of slag from each hut was loaned by Torquay Natural History Museum.	Possibly prehistoric, but the slag in Hut 4 was associated with a coin from the reign of Henry VII and pottery that was unlikely to date from later than AD 1400.
Nosworthy Left Bank (SX56786958)	3/16 3/17	From the collection of Dr Tom Greeves. Found in the riverbank on 26/7/02.	Blowing house, possibly Mediaeval/ Post-Mediaeval. A documentary reference in 1511 to a tin stamping mill by Leder Torre may refer to one of the two mills at Nosworthy, but equally may imply an as yet unknown mill in the vicinity of Leather Tor Farm.
Outer Down (SX68218658)	4/18	From a scatter of slag concentrated in an area several metres from the doorway of the mill, on the adjacent slope to the north. Collected by the author on 17/8/94. (Five pieces of slag were found at Outer Down by Dr Greeves on 22/4/77 and were lodged in Plymouth City Museum (Accession No 94). Two of these were taken for analysis by Tylecote (Tylecote et al 1989).)	Blowing house, pre-1700.
Retallack (SW732300)	4/01 4/02 4/03	Provided by Chris Kelland. Collected in March 2004 from the stream running beside the complex of tin mills.	Blowing house. Documentary evidence indicates smelting on site by 1506. Smelting continued until at least 1545.
Riddon (SX67387671)	2/38 2/39	Two of three pieces of slag found on 19/2/76 by Dr Tom Greeves. Loaned by Plymouth City Museum (Accession No 93 box 3).	Blowing house. Probably Mediaeval.

South Hill I (SX68018710)	2/42 2/43	Loaned by Plymouth City Museum (Accession Nos 112 and 114). Collected by Dr Tom Greeves on 10/9/77 from a deposit of around a hundred pieces in the immediate vicinity of Mill I, and on 26/4/83 from eroded ground on the left bank of the South Teign river at the side of the mill.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
South Hill II (SX67838685)	2/17	From the collection of Dr Tom Greeves. Sample found in June 1993 in disturbed ground caused by wind blown tree root, c.15m north west of the head of the wheelpit and east of the mill dam.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Stannon Brook / Hartland Moor (SX64857955)	2/02 2/03 2/04 4/25	Slag found in eroded areas of the steep bank adjacent to the scatter of boulders that indicates the site of the blowing house. Collected by the author on 17/8/94. (Over 100 pieces of slag have been obtained by Dr Greeves from disturbed ground at Stannon Brook, which was visited on three occasions: 17/5/74, 22/11/75 and 13/10/81. These are now lodged in Plymouth City Museum (Accession Nos 96 and 106).)	Blowing house. Probably Mediaeval.
Taw River (SX62059197)	2/15 2/40 2/41	A single piece of slag from the collection of Dr Tom Greeves, found 5/8/01. Loaned by Plymouth City Museum (Accession No 108), from a collection of sixteen pieces found by Dr Tom Greeves on 26/5/86 in the eroding riverbank beside the mill below Taw Marsh.	Blowing house. Documentary evidence for mill in 1535.
Teignhead Farm Blacksmith's Shop (SX63778426)	2/14	From the collection of Dr Tom Greeves. Found on 15/10/95 on the ground surface between the main mill structure and the wall against the river with the mouldstone in it.	Blowing house, possibly Mediaeval/ Post-Mediaeval.

Thornworthy (SX67238443)	2/45 2/46	Loaned by Plymouth City Museum (Accession Nos 105 and 111), from a collection of eighteen pieces found by Dr Tom Greeves on 22/5/77, *c*.8m east of the NE corner of the mill.	Blowing house, probably 16th/17th Century.
Trereife/ Stable Hobba (SW455294)	3/35 3/36 4/21	Slag from a collection of several dozen pieces recovered by Mr Stephen Polglase from the bottom of a trench that had been excavated by building contractors on the site of the smelting works, and which was about to be filled with concrete. Both analyses are from opposing faces of the same piece of slag. Sent by Mr Bryan Earl. Slag can be found at the sides of the track leading to the cottages west of the entrance to the Stable Hobba Industrial site.	Smelting works with four reverberatory furnaces. Established by 1732; closed 1896. The smelting works was built on or close to the site of Trereiff House, a blowing house that was built after 1660 and is listed as being in operation in 1739.
Trevellas Porth, St Agnes (SW7261351923)	4/19	One of approximately 20 pieces of slag provided by Mr Adam Sharpe of Cornwall Archaeological Unit that were collected from the beach below the mill, which is sited on the northern bank of the stream at its outflow. Slag is plentiful in the stream and on the beach, and small quantities can be found within the mill in places where the soil is eroded.	Blowing house, probably 16th/17th Century.
Wallabrook (SX67207489)	3/18	From the collection of Dr Tom Greeves. Found on the left bank of Wallabrook near Barbeny, 17/3/02.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Wapsworthy Newtake/ Jack Cloke's Prospect (SX54507980)	2/29	Sample sent by Mr Deric Munro, who, in March 2002, discovered four pieces of slag (including the sample analysed) on a waste heap amongst tin streamworks and a fifth piece on the sloping edge of a pit some 30 m south-east of the spoil heap.	Not known. Tin smelting has not previously been recognized in this part of Dartmoor.

Week Ford (SX66187232)	4/23	Sent by Mr Bryan Earl. (Six pieces of slag were found by Dr Greeves on 19/6/86 in an area about 1m square on the eroded riverbank below the lower mill at Week Ford at the point where the line of the wheelpit outflow joins the river. These samples are now lodged in Plymouth City Museum.)	Blowing house. Documentary evidence for a mill operating in 1608. Possible 15th Century pottery also found on site. Mill mentioned in 1737 but may not have been functioning.
Weir Quay (SX434651)	2/18	From the collection of Dr Tom Greeves. Found on the foreshore of the River Tamar in 1996 at SX432649.	Smelting house with reverberatory furnaces established 1849, closed 1890.
Whitten Knowles (SX58596696 approximately)	2/36	Loaned by Plymouth City Museum (Accession No 107), from a collection of over twenty pieces recovered by Dr Tom Greeves on 31/5/84 from a building at Whitten Knowles Rocks that was cut by Longstone Leat and had suffered damaged due to the clearance of the leat.	Not known. Possibly early.
Lower Yealm Steps (SX61796352)	2/13 3/31 3/32	From the collection of Dr Tom Greeves. Found 25m downstream of the mill complex, close to left (east) bank of the river, where a stony heap and pathway are eroded at a point where the path fords the river.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Upper Yealm Steps (SX61726385)	2/10	From the collection of Dr Tom Greeves. Found outside the mill within 10m of entrance, on 9/8/92.	Blowing house, possibly Mediaeval/ Post-Mediaeval.
Yellowmead (SX57426755)	2/44	One of three pieces of slag found on 6/8/85 by Dr Tom Greeves in turf on top of an eroding field wall, approximately 9m north-north-west of the mill. Loaned by Plymouth City Museum.	Blowing house. There is an indirect reference to smelting in the area in 1502.

Yes Tor Bottom (SX56697295)	2/60	Loaned by Plymouth City Museum (Accession No 856). Slag was found during the excavation of prehistoric hut circles by the Dartmoor Exploration Committee of the Devonshire Association (Baring-Gould et al 1898) in the hut closest to the former railway line. Six pieces were retained.	Possibly Bronze Age, but the slag was associated with pottery that may date to 14th/15th Century.

2.1.2: Tin Ores

The archaeological record is poor in regard to tin ores, both because they are often very difficult to recognize and because they tend to be used up in the smelting process. Seven samples from six different sites have been obtained for analysis. Details are presented in Table 2.2.

Table 2.2: Source of Archaeological Tin Ores

Site	Sample	Source	Date and Type of Site
Caerloggas (SX01705659)	4/12 4/13	Two pebbles found within a Bronze Age ring banked enclosure, during excavations led by Miles (Miles 1975). Loaned by Royal Institution of Cornwall Museum, Truro. This sample was previously analysed by Biek (1978).	Bronze Age ritual deposit. One pebble was found in the ditch silt and the other in the basal levelling turfs of a ritual enclosure, together with slag and a dagger fragment.
Chysauster, Gulval (SW472350)	4/30	One large pebble of tin ore found in House 5, during excavations of an Iron Age settlement (Hencken 1933). Its surface artificially worn as though it has been used as a hammer stone. Loaned by Royal Institution of Cornwall Museum, Truro.	An Iron Age courtyard house settlement, with no obvious evidence for metalworking on site.
Crift Farm (SW067602)	4/11	A single piece of cassiterite found on the spoil heap generated by the excavation of the site being carried out by Bradford University.	Probable pre-blowing house smelting. The sample was found in the vicinity of an early Mediaeval longhouse. Dating evidence suggests the site was in use some time between 10th and 14th Centuries.
Dean Moor (SX678653)	3/48	A single pebble of alluvial cassiterite was discovered trodden into the floor of hut 5B at the prehistoric settlement site during excavations carried out between 1954 and 1956 (Fox 1957). Loaned by Exeter City Museum (Accession No 44/1957).	Late Bronze Age settlement site.

Upper Merrivale (SX55197664)	4/10	The sample was provided by Dr Tom Greeves, collected from an ore dump outside Mill B during the excavation of the mill complex by the Dartmoor Tinworking Research Group between 1991and 1996.	Blowing house. Probably 16th/17th Century.
Metherel (SX66828402)	4/14	Sixteen rounded pebbles, identified as tin ore by the excavators, were found along with some slag in Hut 3 during excavations of the prehistoric hut circles at Metherel by the Dartmoor Exploration Committee of the Devonshire Association in the 1930s (Worth 1935; 1937). One pebble was loaned by Torquay Natural History Museum (Museum Reference: A 1995 Box 31).	Possibly prehistoric, but slag in another of the huts was associated with a coin from the reign of Henry VII and pottery that was unlikely to date from later than AD 1400.

2.1.3: Furnace Wall Material

Single examples of furnace wall material from a small number of sites are known, but owing to their rarity in the archaeological record, there is a reluctance to subject such samples to destructive analysis.

Specimens from the collection of Dr Greeves, amounting to a single fragment each from the sites of the tin mills at Avon Dam (SX67226553), Eggworthy (SX54357183) (this slagged and vitrified stone being the only piece of slag that is known from the Eggworthy mill), Week Ford (SX663723) and Taw River (SX62059197) have been examined visually (see Section 3.3.1). (Greeves (pers comm.) also reports having found a single specimen of furnace wall material at Longstone (SX56006876), but this was not available for examination at the time of the visit.)

An examination was also made of specimens collected by Dr Greeves and subsequently lodged in Plymouth City Museum: a single piece from the immediate vicinity of South Hill Mill 1 (SX68018710), collected on 10/9/77; a single piece from Thornworthy (SX67238443) found on 22/5/77; two pieces of slagged granite that had clearly been broken off a large in situ block, and were found loose within the debris of the reverberatory furnace at Eylesbarrow (SX59196765) (Accession No 125), and also from Eylesbarrow a piece of slagged firebrick (Accession No 126) collected on 22/3/77.

Several pieces of slagged and vitrified rock - mainly but not exclusively granite - that are believed to be furnace wall material, were found during the excavations of the Upper Merrivale tin mills (SX55197664) by the Dartmoor Tinworking Research Group. A selection of this material was provided for analysis.

A piece of burnt clay, thought to be possible furnace lining, was dug up from the garden of Blowing House Cottage at Godolphin (SW60333205) by the owners of the property. It was found about 60cm below the surface of the lawn on the north side of the 'blowing house' and was passed to Dr T Greeves on 20/2/04. A portion of this material was supplied for analysis. (A similar slab was shown to the author during a visit to Godolphin in July 2003, although this example was not slagged, and appeared to be plain clay only. The property owner stated at that time that a substantial quantity of this material lay beneath the lawn.)

Pieces of slagged granite from Crift Farm (SW067602) have previously been studied (Aylett 1996).

2.1.4: Tin Metal

A total of nine samples were obtained, deriving from three sites. No analysis has previously been carried out on any metal from Upper Merrivale or Trevellas Porth, but material from Carloggas has been analysed previously (Threipland 1956). Results of the analysis are presented in Table 2.3.

Table 2.3: Source of Tin Metal Samples

Site	Sample	Source	Date and Type of Site
Carloggas / St Mawgan in Pyder (SW874654)	4/29	A fragment of material labelled 'Lead?/Tin? Slag, House W (3) STM/49' from the excavation carried out by Threipland (1956). Loaned by Royal Institution of Cornwall Museum, Truro.	A settlement site believed to have been occupied from the beginning of the 1st Century until about the middle of the 2nd.
Upper Merrivale (SX55197664)	4/32 4/33	Two pieces of corroded tin metal that were discovered beneath the furnace during the excavation of the mill complex by the Dartmoor Tinworking Research Group between 1991 and 1996. Samples provided by Dr Tom Greeves.	Blowing house. Probably 16th/17th Century.
Trevellas Porth, St Agnes (SW7261351923)	3/46 4/31	One of five pieces of metallic tin provided by Mr Colin Wills of Blue Hills Streamworks, found on the beach below Trevellas Coombe. A single piece of metallic tin found on the beach below Trevellas Coombe. Loaned by St Agnes Parish Museum, where it is normally on display (Accession No SAGMT 2003.42). Permission to section this specimen was not granted.	Blowing house. Probably 16th/17th Century.

2.2: Methods of Analysis

2.2.1: Analysis of Slags

All the slag acquired for this study was initially examined by eye, taking note of the following: colour and lustre; the effect of weathering; the presence or absence of mineral inclusions, vesicles and metallic prills; the type of fracture; the size and morphology of the sample.

Images of the samples were obtained using various methods: conventional film photography, digital photography and a Hewlett-Packard flat-bed scanner. The images are presented in the Image Gallery, File 1 (see CD-ROM).

The samples that were selected from larger assemblages to undergo more detailed study were first subjected to qualitative analysis by X-ray Fluorescence in order to confirm or refute the presence of tin. The machine used was a Philips PV9100 (rhodium tube, Si-Li drift detector, operating voltage 40kV, current 200 μA, livetime 200-250s).

The confirmed tin slags were subsequently mounted in cold-setting resin, polished with graded papers and diamond pastes down to 1μm, and examined under an Olympus optical microscope at a range of objective magnifications between 2.5x and 40x. The presence of mineral inclusions and metallic prills was noted, as was the appearance of the slag matrix, particularly with regard to any chemical phases that were visible. Digital images of the surface of the sample were obtained. These are presented in the Image Gallery, File 2 (see CD-ROM). Images were recorded digitally using Fire-I imaging software and Adobe Photoshop 7.

The samples were then carbon coated and studied using a Cambridge Stereoscan 250 scanning electron microscope (20kV, filament saturation, 3 Amps, WD = 25mm, raster scan) running in conjunction with Oxford Instruments Link Isis software. Both normal beam and backscattered electron imaging at magnifications up to 1000x (which covers an area measuring 160 μm by 100 μm) were undertaken, the latter revealing or enhancing features characterized by differences in composition.

The chemical compositions of the mounted samples were then determined on the SEM on the normal beam setting using Energy Dispersive X-ray analysis. Six area scans of each sample were made on 1000x magnification to obtain quantitative data for the bulk composition of the slag at points across the surface of the sample. The area scans avoided visible tin prills (>5 μm) and therefore represent the slag composition. The results of the six individual scans are presented in Appendix 4. Mean compositions are given in Table 3.2 in Section 3.1.4.1. Further quantitative analysis was carried out on many of the samples with the aim of determining the distribution of elements within any chemical phases present (Appendices 5 to 9), identifying the minerals present as inclusions (see Table 3.9 p298) and determining the purity of metal trapped as prills (see Table 3.10 p299).

2.2.2: Analysis of Ores

All the ore samples were examined by eye and with a hand lens, with note being taken of the size and shape of the specimen, the amount of weathering to which it had been subjected, and the types and crystal sizes of any minerals present.

Images of the samples, which are presented in the Image Gallery, File 3 (see CD-ROM), were obtained using digital and conventional film photography.

Images of some of the ores were also obtained using an optical microscope. These are shown in the Image Gallery, File 4 (see CD-ROM).

The samples were subjected to different methods of analysis based upon what limitations were placed upon the author by the owners of the specimens.

Permission was granted to section and polish the samples from Caerloggas, Crift Farm, Dean Moor, Upper Merrivale and Metherel, and subsequently the compositions of these samples were determined using EDX-SEM with the Cambridge Stereoscan 250. Samples were carbon coated for analysis and up to six area scans were made in order to determine the bulk composition of the ore. The size of the scan area was varied to take into account the size of the sample and obvious changes in mineralogy. Results of the individual scans are presented in Tables 3.14 to 3.19. Where possible, additional analysis of individual crystals was carried out.

For the samples from Carloggas and Chysauster, which it was not possible to section and mount, the bulk composition of the ore was studied using Laser Ablation Induction Coupled Plasma Mass Spectrometry, though only semi-quantitative data was obtained. The other ore samples were also analysed by this method for comparison.

Analysis was carried out using a PlasmaQuad 3 ICP mass spectrometer with a Merchantek EO laser ablation system (NIST 613 and 611 standards, energy 75%/mJ, 12 minutes total run time) and ThermoElemental-PlasmaLab analytical software.

An area suitable for ablation was selected using the system microscope and three sets of data were collected from each area during a single run of the laser. A mean for each run was subsequently calculated. Data is presented in Table 3.20 and Appendix 10.

Finally, the mineral content of all the samples (with the exception of the Dean Moor ore) was studied using powder X-ray Diffraction. A small fragment of each of the ore samples was ground to powder using a pestle and mortar. The samples were then analysed using a Bruker D8 diffractometer (wavelength of X-rays 0.154nm, Cu source, Voltage 40kV, filament emission 30mA). Samples were scanned from 5-90° (2θ) using a 0.01° step width and a 1 second time count. The receiving slit was 1° and the scatter slit 0.2°. Spectra and results are given in Section 3.2.2.

2.2.3: Analysis of Furnace Wall and Lining Materials

The samples of furnace wall material were examined by eye and using a hand lens, with note being taken of the type of rock to which the slag adhered, the thickness of the slag, and the amount of vitrification that had occurred. Images of the samples were obtained using conventional film photography and these are presented in the Image Gallery, File 5 (see CD-ROM).

Permission was granted to carry out destructive analysis on some of the specimens of furnace wall material from Upper Merrivale. Four pieces were cold mounted in resin and then sectioned with an industrial stone cutting saw to expose both the outer slagged edge and the inner vitrified granite of the samples. The sections were polished using graded papers down to 1 μm. The samples were not carbon coated.

Normal beam electron imaging and X-Ray mapping was carried out using a Fei Quanta 400 scanning electron microscope with an Oxford Instruments INCAx-Sight EDX system. X-ray maps were obtained to show the distribution of tin (Lα1 peak), calcium (Kα1 peak) and silicon (Kα1 peak) within the samples; from this the extent to which slag penetrated into the granite could be determined and traces of any clay lining material detected.

Energy dispersive X-ray spectra were collected to provide qualitative compositional data.

Subsequently a single sample was carbon coated and fully quantitative EDX-SEM analysis was carried out, see Table 3.24.

Fragments from the slab of clay-like material from Godolphin were analysed using EDX-SEM (Cambridge Stereoscan 250) and ICPMS, see Tables 3.25 and 3.26.

2.2.4: Analysis of Metallic Tin

The samples of metallic tin were examined by eye and using a hand lens, with note being taken of the size and shape of the specimen, colour and lustre, and the appearance and thickness of any corrosion present.

Images of the samples, which are presented in the Image Gallery, File 6 (see CD-ROM), were obtained using digital and conventional film photography. Images of one of the Trevellas Porth samples, obtained using the optical microscope, are also presented (Image Gallery, File 7 (see CD-ROM)).

The specimens of metallic tin were analysed using ICPMS to obtain semi-quantitative data for their bulk composition. Three data sets were collected for each run, and a mean calculated. Analyses were made of the interior and exterior portions of each sample where possible. Additionally, where different phases appeared to be present in the metal, further runs were made to obtain data from these areas. A summary of these results is given in Table 3.30. Full data is presented in Appendix 11.

Further analysis was then carried out using the most appropriate method based upon the condition of the sample and the limitations imposed by the owners of the specimens.

Sample 3/46 from Trevellas Porth was sufficiently solid to be sectioned with a diamond wafering blade and permission to cut this specimen had been granted. Half of this sample was mounted in cold setting resin and polished using graded papers and diamond pastes to 1μm, before being analysed by EDX-SEM. Data was obtained from twelve points across the surface of the sample and from phases visible in the interior, see Tables 3.28 and 3.29.

Samples that had a powdery consistency were not suitable for EDX-SEM analysis, so a small amount of each specimen was ground finely in a pestle and mortar and analysed using X-ray diffraction. Analytical results for tin metal are presented on p371.

2.3: Assessment of Analytical Techniques

2.3.1: X-Ray Fluorescence

This technique has been used only qualitatively, as an indicator of the presence or absence of particular elements. The areas of peaks within the X-ray spectra are not representative of the relative proportions of elements present as some elements produce X-rays more readily than others. In addition the size and density of a sample affects the amount of absorption of X-rays of different energies.

Elements with small atomic numbers (e.g. sodium, magnesium) require the system to be under vacuum if sought.

Where two different elements produce X-rays of similar energies, it may be difficult to resolve the individual peaks. This is often a problem with low atomic number elements that have K lines that are overlapped and swamped by the L and M peaks of higher atomic number elements. Table 2.4 summarizes the peaks that are particularly problematic for the material under consideration here.

Table 2.4: Energies of main X-ray peaks that overlap in spectra of tin slags

Element and X-ray line	Energy keV	Element and X-ray line	Energy keV
W M_{α}	1.77	Si K_{α}	1.74
Sn L_{α}	3.44	K K_{α}	3.31
Sn $L_{\beta 1}$	3.66	Sb L_{α}	3.60
Sn $L_{\beta 1}$	3.66	Ca K_{α}	3.69
Sn $L_{\beta 2}$	3.90	Sb $L_{\beta 1}$	3.84

In addition, the X-ray production tube within the machine produces a large peak for the element rhodium that may potentially mask elements with peaks at adjacent energies.

2.3.2: Energy Dispersive Scanning Electron Microscopy (EDX-SEM)

Scanning electron microscopy allows elements to be detected at levels down to 0.1% by weight under ideal conditions. As with X-ray Fluorescence techniques, when analysing complex mixtures such as slags there are issues relating to the resolution of coincident peaks. The fact that each element produces multiple peaks, and that there is a theoretical fixed relationship between the relative sizes of the peaks in the K, L and M series (if present) for each element, allows sophisticated software to resolve these elements. However, in such cases the limit of sensitivity should thus be considered as 0.5%, for while it is possible to resolve peaks, differential absorption of X-rays of different energies may in practice mean that the peak-size relationship does not hold true, so there remains a certain level of doubt in any quantitative analysis where a smaller peak is overlapped by one that is larger.

The conversion of X-ray peak area to percentage concentrations by weight introduces another potential source of error. The calculation performed by the analyser software is not straightforward and the result obtained is dependant upon the oxidation state in which any particular element is present.

As several of the elements contained within the samples under consideration are capable of existing both in the metallic form and as the oxide, the concentrations obtained would vary greatly depending upon whether the calculation was based upon

atomic weight or oxide weight. In the case of slag, the presence of metallic prills within a matrix composed of oxides can cause a difficulty. As far as possible, when bulk analyses of the slag matrix were made prills were avoided but where samples contained large numbers of extremely small prills this was not always wholly possible. To complicate matters further, some of the elements under consideration may exist in two or more different oxidation states, e.g. iron, tin and tungsten. Given that tin smelting requires reducing conditions, it has been assumed that tin would be present in the slag as the Sn^{2+} ion, i.e. as SnO, as opposed to the Sn^{4+} ion, i.e. as SnO_2. (Although EDX-SEM results are quoted as oxides, in reality the tin is most likely to be in the form of a silicate). However, in practice, it is likely that tin is present in both oxidation states and also as metal. This is also a reasonable assumption for the samples of smelted tin metal, as, in all cases, the original metal appeared to have undergone some re-oxidation. In ores the tin is almost certainly in the form of SnO_2.

Summing the percentage concentrations of all the elements present can provide a guide to the validity of the assumptions made regarding the choice of oxidation state. Assuming that all other sources of error have been minimised, and allowing a 5% margin for machine error, a total of 100% should be attained.

Finally, it should be borne in mind that the analyser only determines the concentrations of those elements that it has been instructed to seek, and thus it may be possible that other elements are present within a sample. However, it is possible to detect these by using the software to compare the real X-ray emission spectrum with the spectrum of a theoretical slag with the composition determined by the analyser. In practice, the observed differences were so small that they fell within the experimental limits of the analyser.

Determinations of the concentration of elements within prills and mineral inclusions, or of separate phases within the slag, may be subject to errors caused by differential penetration of X-rays of different energies. It is not possible to gauge the thickness of any feature observed within a slag sample and thus it is possible that, in features that are very shallow, elements from the underlying slag matrix could be detected. In order to minimize this problem, only the largest of the available features were selected for analysis. In addition, since sectioned prills tend to be hemispherical, scans were made of the centre of prills, where the depth of material could be assumed to be greatest.

Difficulties also arise when attempting to detect differences in composition between layers within a sample that have very similar compositions: for example, the areas observed in the Trevellas Porth tin sample, observed very clearly using the optical microscope, were much harder to distinguish using the scanning electron microscope.

2.3.3: Induction Coupled Plasma Mass Spectrometry (ICPMS)

This technique does not normally allow individual crystals to be analysed owing to their relatively small size in comparison to the area that is ablated by the laser. With the exception of some of the phases observed in the samples of metallic tin, which were of sufficiently large size to enable them to undergo individual analysis, the results obtained from the spectrometer were thus representative of the bulk composition of the samples only.

The ICPMS has problems with mass bias, which results in the best precision for elements with heavier mass, lighter elements giving poor measurements.

Glass standards are used to calibrate the spectrometer, and ideally these should contain all the elements of interest as are present in the samples, each at different

concentrations. However, such standards are not available, meaning that the machine is only partially calibrated and therefore fully quantitative analysis is not possible.

Additionally, determinations of some elements can only be made semi-quantitatively owing to the nature of the device. For example, iron suffers polyatomic interference from the argon gas providing the supposedly inert atmosphere within the machine, but which in fact can be oxidized to the ArO^{+} ion (mass 40 + 16), equal to that of the Fe^{26+} ion (mass 56). There is also the problem of isobaric interference, caused by the presence of different elements with isotopes of the same mass, e.g. argon and calcium both have common isotopes with a mass number of 40. An extreme case is encountered for mass number 115, and as a result indium has not been sought since this element is almost entirely swamped by the presence of the tin isotope $^{115}_{50}Sn$.

Another difficulty in obtaining quantitative data comes from the fact that the count rate is highly dependent on the type of material being analysed: calibration is made against standard glass samples and the slag, metal and ore samples under consideration may be more or less easily vapourized than the material of these standards, thus affecting the results. There is also the problem that different components of an individual specimen (for example a metal sample which is composed of un-oxidized metal interspersed with areas of corrosion product) may ablate more readily than others.

Concentrations are here quoted to 1ppm, but limits of detection vary for each element and given the uncertainties introduced by the unevenness of ablation, and difficulties with calibration, in reality this level of precision cannot be achieved. Even for elements present in the glass standard, the detection limit should be considered to lie in the range 5 - 150ppm.

Large negative values, which occur as a result of uncertainties in calibration, are quoted as 'not quantifiable', and small negative values have been quoted as zero.

Where extremely large numbers of one particular ion are liberated during ablation the spectrometer may be overwhelmed and no quantification will be possible in such circumstances. This was a particular problem with the determination of the amount of tin present in the metal samples.

During analysis blank runs (i.e. without standard or sample) were carried out to monitor for laboratory contamination, and the standards were periodically re-run to monitor machine drift.

2.3.4: X-Ray Diffraction

This technique utilizes analytical software to match the peaks of a diffraction spectrum for a sample with the ideal spectrum for a particular mineral. The first difficulty with this method arises from the fact that there are slight variations in the crystal structures of many compounds: the atoms of cassiterite, for example, can be present in at least four possible arrangements, each arrangement producing a slightly different spectrum. An exact match between sample and ideal does not usually occur, therefore, but in such cases the majority of the good matches generated by the computer will be different versions of the same mineral species and so the identification of the compound is not usually in doubt.

Further complications result when the sample under consideration is not composed of a single mineral: the problem is particularly acute in the case of the ore samples owing to the complexity of these materials. All the ores contain a suite of minerals present in varying quantities, and the spectra generated are thus composites. The

software is led to present several, often vastly different, mineral species as possible matches, requiring the operator to make a semi-subjective selection of one or two using prior knowledge of the bulk composition of the sample gained through other analytical techniques.

Owing to the differential sensitivity to particular mineral species, the limits of detection for the instrument vary between 5 and 15%.

Chapter 3

Results

3.1: Results of Slag Analysis

3.1.1: Physical Characteristics of Tin Smelting Slags

Tin smelting slags may be characterized in terms of their size, morphology, the extent of weathering, their colour, lustre, and the type and quantity of inclusions. A description of selected slag samples is presented in Appendices 3a and 3b, and photographs of slags are presented in the Image Gallery, File 1 (see CD-ROM). Some general trends may be observed.

When considered *en masse* it is apparent that specimens come in a range of sizes from grain-sized fragments to slabs with masses of over a kilogram. Although slag may suffer breakage in the burial environment, it nevertheless appears that the mass of slag produced increases as one moves closer to the present day. Early slags and samples from blowing houses tend to have masses of a few grams, whilst reverberatory slags may have masses of kilograms. There are a few exceptions to this, however: some of the specimens collected from Upper Merrivale blowing house have masses of several hundred grams and are of comparable size to some of the reverberatory specimens.

Slag samples obviously come in a vast array of different shapes, both because they have solidified from more or less viscous liquids that may have been flowing, and because they were subsequently subjected to breakage, either deliberately or in the burial environment, and in this latter case, of course, their original size and shape cannot be determined. The Bronze Age slag from Caerloggas appears to have formed as a thin layer, which possibly overlay molten tin. There are also examples of blowing house

slags (Lustleigh, Wapsworthy) with flat upper and lower surfaces and broken edges, which may originally have formed part of a slag layer. This feature can also be observed in some reverberatory slag samples (e.g. Trereife). Layer formation is suggestive of a slag that was either very fluid or was left to settle for a relatively long period. By contrast, many of the earlier slags (e.g. Ditsworthy, Lether Tor Farm) appear to have been high viscosity melts, as they exhibit clear flow morphologies: they have ridged surfaces, often appear rod-like, and solidified droplets can be observed. Many of the samples from Crift Farm take the form of rods, usually 1 or 2 cm long, with a roughly circular cross section of c.1cm diameter. Occasionally the slag has a roughly crescent-shaped cross section, such as would form if a sideways force was applied to a thin stream of viscous slag: this may be evidence for skimming of the slag from a float.

When freshly exposed, all tin smelting slag is dark in colour: the vast majority of samples appear black; a very few early slags, such as those from Caerloggas and some examples from Crift Farm are a very dark brown, and occasionally lighter brown streaks can be observed within the dark brown or black slag suggestive of incomplete mixing of the different mineral species that made up the ore; some slags, often those that occur as large slabs, are dark grey (e.g. Upper Merrivale, Trereife).

The vast majority of the slag samples examined had the appearance of dark glass, regardless of date or method of smelting. Within this group were several samples that exhibited conchoidal fracture, indicating that they were indeed glassy.

A smaller proportion of the slags had a silky lustre. These samples included a few blowing house slags (e.g. Yealm Steps, Upper Merrivale) and reverberatory slags (e.g. Trereife, Weir Quay). Rare examples of matt slags have been observed (e.g. Wapsworthy, Upper Merrivale). As will be seen later, the lustre of the slag is dependent

upon its microstructure, and there is an apparent link between form and lustre: silky and matt samples often have forms that suggest a low viscosity slag, while glassy slags often have morphologies consistent with high viscosity melts.

It is worth noting that there can be very great differences between samples from an individual site: examination of the abundant slag from Upper Merrivale revealed that samples ranged from millimetre sized fragments to slabs as large as those found at $18^{th}/19^{th}$ Century reverberatory smelting sites; glassy, silky and matt slags were all present; slab-like samples from highly fluid melts and morphologies indicative of high viscosity melts were both observed. However, the much more limited range of variation seen at Crift Farm, which is the only other site for which very large numbers of samples are available for analysis, suggests that earlier slags may be more uniform.

Many of the slag samples examined had undergone weathering of their outer surfaces, and only in those cases where more recent breakage had occurred could the true nature of the slag be seen. Weathering generally causes slag to become a dull dark grey, but several examples have been observed where the surface is stained red-brown with iron oxide (Thornworthy, Lower Yealm Steps). More rarely, the surface may weather to a dark gold. This was first noted on the Caerloggas slag samples by Biek (1978) who described it as a 'thin golden iridescent flaky skin of 'hydrogen glass' i.e. largely silica'. It is present on some samples from Whitten Knowles and Crift Farm, but also on about 10 samples from Upper Merrivale; thus it appears to occur mainly, but not exclusively, on early slags. Lastly, weathering may cause a blue sheen to appear on the outer surface of the slag. Only two examples are known: one from Upper Merrivale, the other from Week Ford. The composition of this substance has not been determined.

In addition to the slag matrix, samples may contain features such as vesicles, mineral inclusions, prills of trapped metal, and fragments of fuel from the furnace. That these are observed is a matter of chance, as they are randomly distributed within the slag and will only be exposed if the slag is broken where they occur.

Vesicles are very common and occur in a range of sizes from sub-millimetre up to several centimetres. They are indicative of gas flow through the slag, and may provide a means to determine the composition of the atmosphere within a furnace, but to date no attempt has been made to sample the gas within vesicles. Blowing house slags tend to be more vesicular overall than reverberatory slags, but some reverberatory slags do contain vesicles and these can be relatively large.

Mineral inclusions are also very common, mainly in blowing house slags, although a few rare and unexpected examples have been noted in reverberatory slags. These inclusions probably derive mainly from the ore, and thus indicate that the separation of gangue and ore minerals was not fully successful. However, slag/furnace-lining interactions may also cause some mineral fragments to enter the slag. There is also the possibility that minerals from old furnace linings that have been recycled back to the furnace have persisted. The inclusions are randomly scattered within the slag matrix and appear as sub-rectangular or sub-rounded grains of pale grey or cream, the edges of which often appear to be blending into the slag. In size they range from sub-millimetre specks to chunks several centimetres across; the latter may be pieces of the body of the furnace that have reacted with the slag rather than residual minerals from the ore.

Occasionally beads of trapped metallic tin can be observed. In fact, the phenomenon is rather common, but owing to the very small size of the vast majority of these prills they cannot usually be viewed with the naked eye. Prills occur in slags of all types, but

examples of millimetre size seem to occur most frequently in early slags. Most prills are spherical, but very rare occurrences of irregular-shaped prills are known.

It is incredibly rare for pieces of fuel from the furnace to become trapped within the molten slag and be preserved, but a single example of this was discovered at the Upper Merrivale site, and suggests the use of wood charcoal in the furnace there.

3.1.2: Optical Microscopy of Slags

Previous examinations of slags by optical microscopy (Worth 1937; Tylecote 1965, 1966; Malham 1996), as well as investigations using scanning electron microscopy (Biek 1978; Tylecote et al 1989; Adriaens 1996; Malham 1996, 2002; Salter 1997) (see Section 1.2.1) revealed that tin slags might be fully glassy, contain fine phases, or be fully crystalline. They also commonly contain trapped droplets of metallic tin and mineral inclusions.

Optical microscopy of the new samples selected for examination confirmed that tin slags exhibit a range of different microstructures. Some samples were completely glassy e.g. Lingcombe 3/19 (Figure 3.1), and many of the glassy samples had striations or 'flow bands' within the matrix e.g. Doe Tor Green 2/12 (Figure 3.2). In other samples several distinct types of phase could be observed: feathery or needle-like phases (which had characteristics suggesting that they were underdeveloped dendrites) e.g. Nosworthy 3/17 (Figure 3.3); dendrites, which could be fine or chunky, or both e.g. Thornworthy 2/45, Thornworthy 2/46 and Drakeford Bridge 2/19 (Figures 3.4, 3.5 and 3.6); and relatively large regular crystals e.g. Upper Merrivale 2/27 (Figure 3.7). In the case of feathery phases and dendrites, the phases could comprise the entire surface of the slag, or could be restricted to isolated areas within an otherwise glassy matrix, such as in sample 2/43 from South Hill (Figure 3.8).

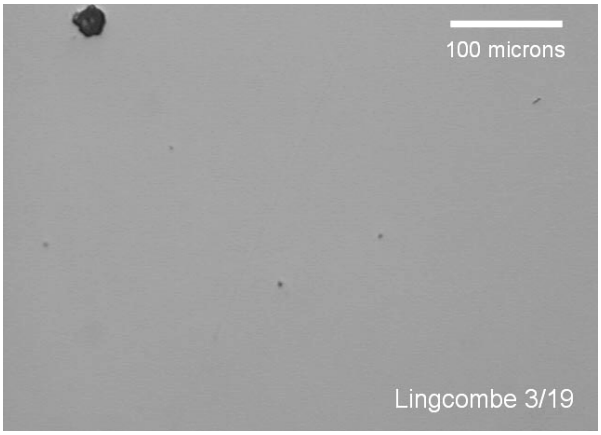


Figure 3.1: Glassy slag from Lingcombe, sample 3/19.

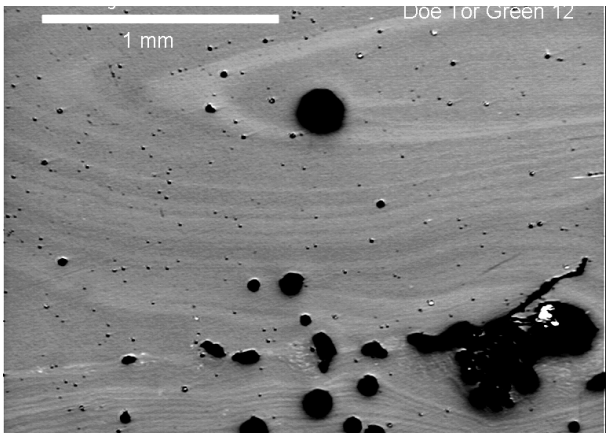


Figure 3.2: Glassy slag from Doe Tor Green, sample 2/12, showing flow banding and several vesicles.

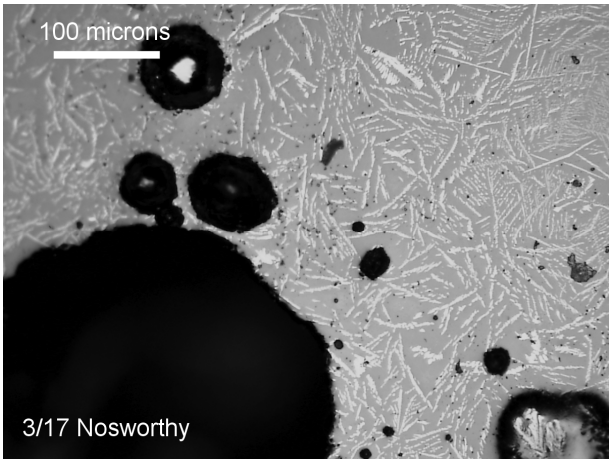


Figure 3.3: Pale iron/titanium rich feather-like phases in vesicular slag from Nosworthy, sample 3/17.

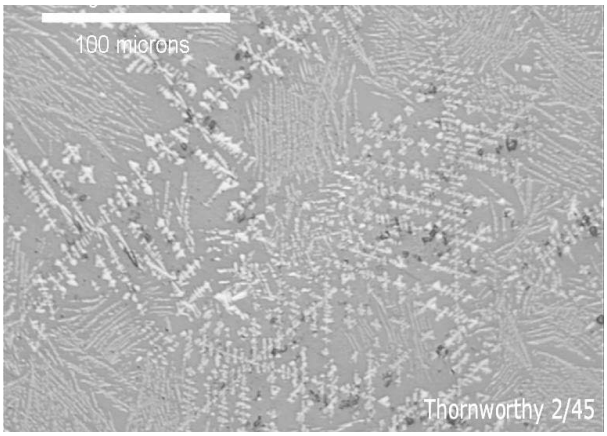


Figure 3.4: Small-size iron/titanium rich dendrites in slag from Thornworthy, sample 2/45.

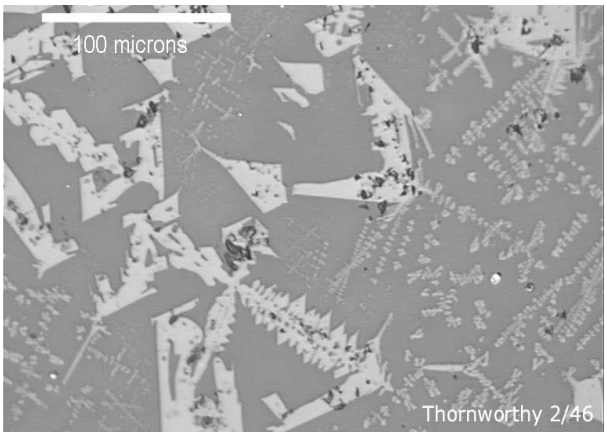


Figure 3.5: Large-size iron/titanium rich dendrites in slag from Thornworthy, sample 2/46.

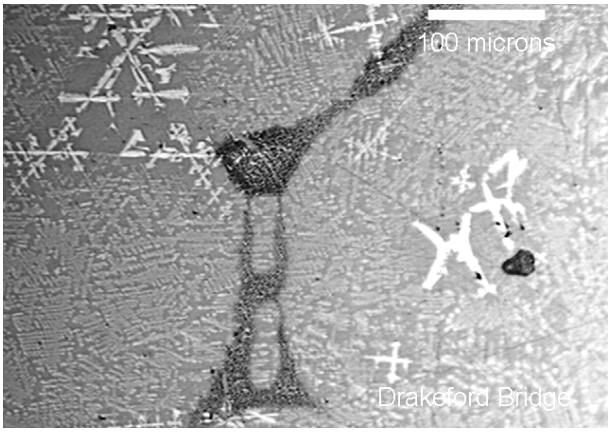


Figure 3.6: Slag from Drakeford Bridge, sample 2/19, showing iron/titanium rich dendrites on two scales.

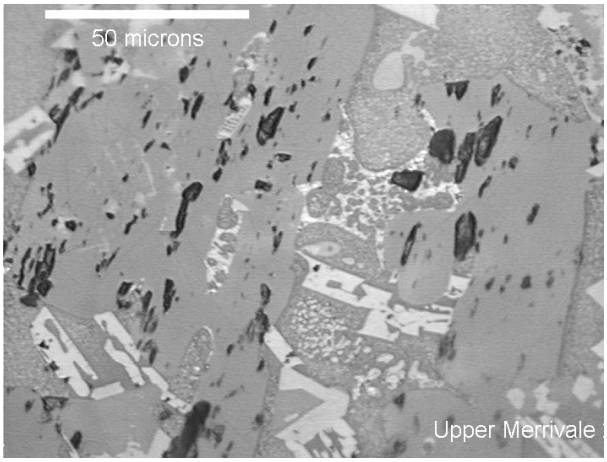


Figure 3.7: Crystalline, three-phased slag from Upper Merrivale, sample 2/27, containing many small elongate vesicles. The light phase is tungsten rich; the surrounding grey phase is tin rich; the darker grey laths are iron silicate.

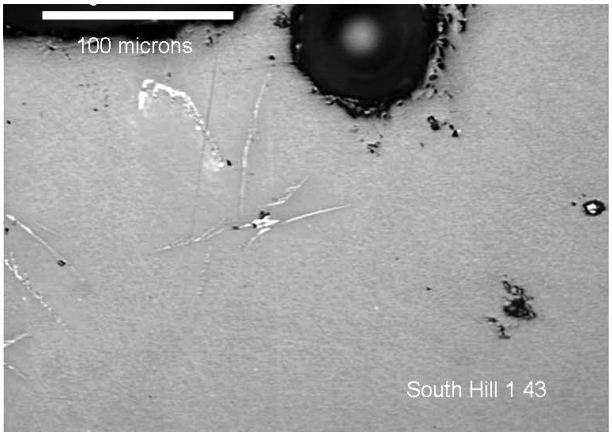


Figure 3.8: Slag from South Hill, sample 2/43, with patches of titanium rich feather-like phase and dark vesicles. The slag in the lower right hand half of the image exhibits a very faint granulation; around the pale phase it is glassy.

The microstructures of individual samples are summarized in Table 3.1. Images of all samples are presented in the Image Gallery File (see CD-ROM).

The range of microstructural forms may be envisaged as a spectrum, with a progression from glassy through feathery phases to dendrites and crystals. Glassy slags and samples with feathery phases generally appear to be glassy when viewed with the naked eye. However, crystalline slags or those with relatively dendrites often appear to have a

silky lustre or can even appear to have a matt surface. How microstructure relates to the composition of the slag is discussed in Section 3.1.4.

Notably, variations in microstructure are seen to occur between different samples from the same site. Nevertheless, with regard to the relationship between slag microstructure and production technology, some general observations can be made.

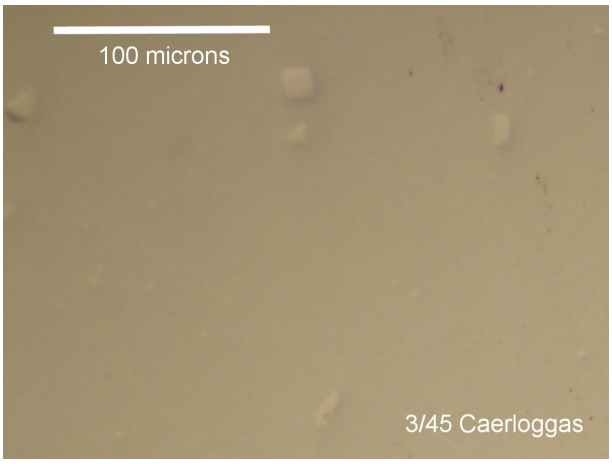


Figure 3.9: Pale angular cassiterite crystals in glassy matrix of sample 3/45 from Caerloggas.

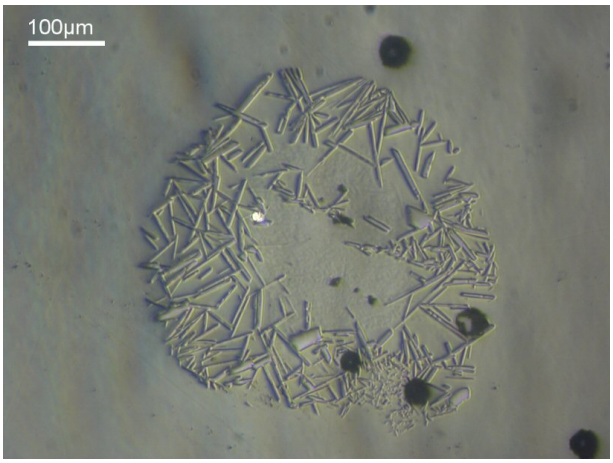


Figure 3.10: Aluminium silicate crystal ring in glassy matrix of sample 4/17 from Crift Farm.

Although the sample size is very small, all undisputed pre-blowing house slag samples examined thus far are glassy. However, there are several examples of these early glassy

slags containing occasional isolated crystals. The sample from Caerloggas contains a few pale c.5μm angular crystals (Figure 3.9), while samples from both Caerloggas and Crift Farm have c.500μm diameter clusters of dark needle-like crystals c.50μm long, some of which are arranged in distinct rings (Figure 3.10). These unusual features have not been reported elsewhere.

Blowing house slags show a very wide range of microstructures, from glassy through to fully crystalline (although this latter is rare), and this appears to some extent to be a geographical phenomenon, with slags from northeast Dartmoor tending to contain more crystalline phases, while slags from Cornwall and more south-westerly parts of Dartmoor are more likely to lie at the glassy end of the spectrum.

Reverberatory slags may also be glassy, dendritic or crystalline. Although again the sample size is very small, there is no geographical relationship observed within this group of samples, and as it is known that ores were transported from mines across Devon and Cornwall, and even from abroad, it is unlikely that such a relationship exists.

Within the slag features such as vesicles, mineral inclusions and prills of trapped metal may be observed. Sub-millimetre scale metallic prills are far more numerous than naked eye prills, and it is notable that prills are particularly common in glassy slags, though they are by no means absent from slags with crystalline phases. At high magnifications it is clear that the mineral inclusions are not simply lodged in the slag matrix but have undergone some reaction with it, so that the edges of the inclusion blend with the slag.

3.1.3: Imaging of Slags using the Scanning Electron Microscope

Imaging of slags using the scanning electron microscope on normal beam confirmed the observations made using optical microscopy, i.e. that slags exhibit a range of microstructures, with more modern slags tending to be more crystalline in nature, and that mineral inclusions and trapped metallic prills occur in slags from all periods. The higher magnifications achievable with scanning electron microscopy permitted smaller crystals to be resolved, thus it was possible to determine that the slightly granular appearance of the slag matrix in parts of samples 2/17 and 2/43 from South Hill (see Figure 3.8), was due to the presence of very tiny <1μm crystals. Other than these samples, normal beam imaging did not reveal any previously unrecognised small-scale features within the slag matrix.

Backscattered electron imaging, which displays contrasts between elements of high and low atomic number, thus distinguishing features of different composition, did reveal additional characteristics that were not obvious using optical microscopy.

Flow banding, which was enhanced in all samples by the technique, was noted in several more samples in which striations had not previously been visible: these are denoted (S) in Table 3.1 below.

The feathery phase in sample 2/15 from Taw River, which appeared paler than the surrounding matrix using optical and normal beam scanning electron microscopy, appeared dark when using backscattered electron imaging. In this respect this sample is unique: feather-phases in all other samples appeared pale using backscattered electron imaging.

Several metallic prills had a mottled or patchy appearance when viewed using backscattered electron imaging, e.g. Doe Tor Green 2/12, Nosworthy 3/16, Retallack

4/01 and Trereife 3/35 and 3/36. Often these were prills that were irregular in shape. This implies that the prill is not composed solely of tin.

The final observation of note is that several of the samples containing one or more crystalline phases appeared to have fewer phases when examined using backscattered electron imaging, which implies that crystals that appear optically dissimilar either have very similar chemical compositions, or contain elements with similar atomic masses such that there is no contrast between different phases. This effect was noted in samples 4/05 and 4/06 from Eylesbarrow, in samples 2/35 and 2/36 from Trereife, and in sample 2/13 from Lower Yealm Steps. For further discussion see p291-4.

Table 3.1: Summary of Slag Microstructures

Abbreviations used: G = glassy, S = striations/flow bands, (S) = faint striations/flow bands, F = feathery/needle-like phase, Dn = dendrites (narrow/fine type), Db = dendrites (broad type), C = fully crystalline, (F) (D) (C) = phase occurring in isolated patches only.

Site	Slag Microstructure	Notable features	Vesicles		Prills		Mineral Inclusions	
			Frequency	Size	Frequency	Size	Frequency	Size
Avon Dam 2/20	GS(F)		Moderate	c.1mm	Moderate Common	c.100µm c.3µm	Moderate	c.500µm
Blackaller 4/22	G(F)(Dn)		Rare	<1mm	Rare (not spherical)	c.10µm	None observed	-
Butterbrook 2/33	FS		Common	c.1mm	Rare (non-spherical and not consolidated)	<1mm	None observed	-
Butterbrook 2/34	G(F)		Common	c.1mm	Rare (non-spherical and not consolidated)	<1mm	None observed	-
Caerloggas 3/44	GS	At high magnification a patch of pale c.20µm needle-like crystals is visible; rare isolated c.10µm pale angular crystals occur elsewhere.	Rare	c.100µm	Moderate	<1mm	None observed	-

Caerloggas 3/45	GS	Under high magnification three 500µm diameter rings, formed of needle-like crystals c.50µm long, are visible. Rare scatters of a few pale <5µm angular crystals occur elsewhere within the matrix.	Rare	c.100µm	Rare	c.50µm	Rare	c.1mm
Carvedras 3/30	C		Rare	c.1mm	Rare (irregular) Moderate (not tin)	c.20µm <10µm	None observed	-
Charlestown 4/20	DnC	Many c.1µm pale spots that may be oxide grains.	Rare	c.50µm	Rare (some irregular)	c.10µm	Rare	c.1mm
Crift Farm 4/15	GS(F)(Dn)		Moderate	c.1mm	Moderate Rare	<10µm c.40µm	Moderate	c.0.5mm
Crift Farm 4/16	GS		Moderate	c.50µm	Moderate Rare Contains a 200 x 100 µm cluster of 1µm prills	<5µm c.40µm	Moderate	c.0.5mm
Crift Farm 4/17	GS	Contains clusters of c.50µm needle-like crystals - at least one cluster forms a ring; clusters measure c.500µm.	Moderate	c.50µm	Rare Common	c.100µm c.2µm	Moderate	c.0.5mm

Crift Farm 4/27	GS		Moderate	c.200μm	Rare Common	40μm c.1μm	Single	c.1mm
Ditsworthy 3/01	GS		Moderate	c.250μm	Rare Moderate	c.100μm <100μm	Moderate	c.1mm
Doe Tor Green 2/12	GS(F)		Moderate	c.100μm	Rare (mottled)	c.100μm	Moderate	c.1mm
Drakeford Bridge 2/19	Dnb		Rare	c.200μm	None observed	-	Single	c.1mm
Eylesbarrow 2/35	C(Db)	Dark matrix with two types of crystal: pale angular type and mid-grey c.50μm needles.	Moderate	c.200μm	c.10μm wide streak runs across sample	-	None observed	-
Eylesbarrow 4/05	C	Contains very small pale crystalline laths. No phases visible using backscattered SEM.	Common	c.100μm	None observed	-	None observed	-
Eylesbarrow 4/06	C	Contains c.10μm pale crystalline laths. No phases visible using backscattered SEM.	Very common	c.1mm	Rare (some irregular)	<20μm	Very common	c.1mm
Glazebrook 2/58	GS(F)		Rare	c.20μm	Rare Moderate	c.500μm c.30μm	None observed	-
Gobbett 2/28	FDn		Moderate	c.50μm	At least four c.200μm clusters of c.5μm prills	-	Common	c.1mm
Hurdon 2/01	GS		Moderate	c.200μm	Common	c.20μm	Single	<1mm
Hurdon 4/26	GS		Very common	c.10μm	Moderate	c.20μm	None observed	-

Lether Tor Farm 2/11	GS		Common	c.500µm	Moderate	c.1mm	Single	<1mm
Lingcombe 3/19	G(S)		Common	c.20µm	Single	c.50µm	None observed	-
Lingcombe 3/20	Db(n)		Common	c.1mm	None observed	-	None observed	-
Longstone 2/06	GS		Moderate	c.500µm	Rare Very common	c.50µm <10µm	Single	<1mm
Longstone 2/07	GS		Moderate	c.500µm	Rare	c.30µm	Single	<1mm
Longstone 2/47	G		Common	c.500µm	None observed	-	Very common	c.1mm
Longstone 4/24	GS		Moderate	c.500µm	Moderate Common	c.100µm c.10µm	None observed	-
Lustleigh 2/50	Dn		None observed	-	None observed	-	None observed	-
Lustleigh 2/51	Db		Very rare	c.100µm	None observed	-	None observed	-
Lower Merrivale 4/04	G(S)		Common	c.50µm	Single Very common	c.2mm c.5µm	None observed	-
Lower Merrivale 4/28	G(S)	One oval area c.600 x 200µm composed of 2-20µm globules of partially reduced cassiterite.	Common	c.500µm	Common	c.5µm	None observed	-
Upper Merrivale 2/21	G (F)		Common	c.500µm	Rare Common	c.100µm c.5µm	None observed	-

Upper Merrivale 2/22	F(G)		Moderate	c.200μm	Rare	<100μm	Single	<1mm
Upper Merrivale 2/23	G(F)		Common	c.1mm	Rare Common.	c.100μm c.5μm	None observed	-
Upper Merrivale 2/24	GS(F)		Moderate	c.50μm	Common	c.5μm	None observed	-
Upper Merrivale 2/25	G(Dn)		Rare	c.500μm	Rare	c.200μm	Moderate	c.1mm
Upper Merrivale 2/26	GS		Common	c.500μm	Rare	c.100μm	None observed	-
Upper Merrivale 2/27	C	3 phases: mid grey matrix, pale elongate crystals, dark grey laths.	Moderate Very common	c.1mm <50μm	Rare	<10μm	None observed	-
Upper Merrivale 2/31	G		Common	<1mm	Single (irregular)	300 x 400μm	Moderate	c.1mm
Upper Merrivale 2/32	Dnb		Common	c.100μm	Rare	c.40μm	Single	<1mm
Upper Merrivale 2/52	G(F)		Common	c.100μm	Common	c.10μm	None observed	-
Upper Merrivale 2/53	GS		Moderate	c.500μm	Rare Common	c.100μm <5μm	Moderate	c.1mm

Upper Merrivale 2/54	F		Common	c.100µm	Rare	c.50µm	None observed	-
Upper Merrivale 2/55	F		Common	c.100µm	Rare	c.20µm	None observed	-
Upper Merrivale 2/56	FDn		Rare	c.100µm	Rare	c.20µm	None observed	-
Upper Merrivale 2/57	FDn		Common	c.1mm	Rare	c.100µm	Moderate	c.1mm
Upper Merrivale 3/24	GS		Rare	c.10µm.	Single	c.30µm	None observed	-
Upper Merrivale 3/27	DnC	A dark matrix with fine pale dendrites and irregular shaped mid-grey crystal laths.	Rare	c.10µm.	None observed	-	None observed	-
Metherel 2/48	GS	At higher magnifications c.5µm pale crystals present, but confined to paler flow bands.	Rare	c.50µm	Moderate Very common.	c.500µm <100µm	None observed	-
Metherel 2/49	G	At higher magnifications entire surface of sample covered in c.5µm pale crystals.	Rare	c.200µm	Moderate Very common.	c.500µm <100µm	None observed	-

Nosworthy 3/16	F		Moderate	c.200µm	Two large (irregular; patchy under backscattered SEM) Common in parts, rare in others	c.1mm 200x400µm c.5µm	Moderate	c.500µm
Nosworthy 3/17	F		Common	c.1mm	None observed	-	Rare	c.1mm
Outer Down 4/18	F(G)		Common	c.1mm	Rare	c.40µm	Moderate	c.1mm
Retallack 4/01	GS		Common	c.500µm	Single (mottled) Common	c.100µm 20µm	None observed	-
Retallack 4/02	GS		Moderate	c.100µm	Moderate	c.20µm	Rare	c.3mm
Retallack 4/03	GS		Common	c.500µm	Rare Very common	c.40µm 20µm	None observed	-
Riddon 2/38	G(Dn)		Moderate	c.500µm	None observed	-	Moderate	c.1mm
Riddon 2/39	GS		Moderate	c.100µm	None observed	-	Moderate	<1mm
South Hill I 2/42	F	Small-scale pale feather-like phases over whole of surface of sample give a granular appearance to the slag; these phases are arranged in a globular pattern, with c.50µm globules.	Moderate	c.200µm	None observed	-	None observed	-

South Hill I 2/43	G(F)(C)	Entire surface appears granular at high magnification: very tiny c.1μm crystals visible using SEM	Moderate	c.500μm	Moderate	c.30μm	Moderate	c.1mm
South Hill II 2/17	G(S)(C)	Entire surface appears granular at high magnification: very tiny c.1μm crystals visible using SEM	Rare	c.200μm	None observed	-	None observed	-
Stannon Brook 2/02	G(S)(F)		Moderate	c.500μm	Common.	c.10μm	Rare	c.200μm
Stannon Brook 2/03	G(S)		Moderate	c.500μm	Common.	c.10μm	Rare	c.500μm
Stannon Brook 2/04	G		Moderate	c.500μm	Common.	c.10μm	Moderate	c.1mm
Stannon Brook 4/25	G(S)		Rare Very common	c.2mm c.10μm	Very common.	c.10μm	Moderate	c.1mm
Taw River 2/15	F	Feathery phase appears pale optically as with other samples; appears dark with backscattered SEM (unusual).	Moderate	c.200μm	Single Moderate	c.150x100μm c.20μm	None observed	-
Taw River 2/40	G(S)(F)		Common	c.200μm	None observed	-	Moderate	c.200μm
Taw River 2/41	GS(F)		Common	c.200μm	Single Moderate	c.50μm c.20μm	Rare	c.200μm

Teignhead Farm 2/14	G(S)(C)	Very rare pale crystals c.20μm.	Moderate	c.200μm	None observed	-	Common	c.100μm.
Thornworthy 2/45	Dn		Rare	c.100μm	Rare	c.20μm	None observed	-
Thornworthy 2/46	CDn		Moderate	c.200μm	Very common	c.3μm	None observed	-
Trereife 3/35	C	Phases optically visible: dark matrix; c.100μm elongated grey crystals; pale sub-rectangular c.50μm crystals; irregular or sub-rectangular c.20μm pale pink crystals; c.5μm circular and sub-rectangular white blobs (not prills). Fewer phases detected using backscatter SEM.	Common	c.100μm.	Two (irregular, patchy appearance)	c.100μm <100μm	None observed	-

Trereife 3/36	C	Phases optically visible: dark matrix; c.100µm elongated grey crystals; pale sub-rectangular c.50µm crystals; irregular or sub-rectangular c.20µm pale pink crystals; c.5µm circular and sub-rectangular white blobs (not prills). Fewer phases detected using backscatter SEM.	Moderate	c.100µm.	Two (irregular, patchy appearance)	c.80x40µm c.50µm	None observed	-
Trereife 4/21	CDn	Some areas contain pale sub-rectangular c.50µm crystals.	None observed	-	None observed.	-	None observed	-
Trevellas Porth 4/19	G(S)		Moderate	c.50µm	Single (irregular) Rare (regular)	c.100µm <50µm	None observed	-
Wallabrook 3/18	F		Common	c.1mm	Rare Very common in certain areas	<300µm c.10µm	Rare	c.1mm
Wapsworthy Newtake 2/29	GS(F)(Dn)		Moderate	c.1mm	Single Common	175x100µm c.20µm	Moderate	c.1mm
Week Ford 4/23	F(C)(G)		Common	c.100µm	Single Rare	c.40x20µm <20µm	None observed	-
Weir Quay 2/18	Dnb		Moderate	c.1mm	None observed	-	Rare	c.1mm

Whitten Knowles 2/36	GS		Moderate	c.500µm	Two	c.40µm	Rare	c.1mm
Lower Yealm Steps 2/13	C	Three phases visible optically: mid-grey matrix with darker angular laths, and small c.20µm pale sub-rectangular crystals. Backscatter SEM shows only dark matrix with angular laths.	Common	c.50µm	Common	c.20µm	None observed	-
Lower Yealm Steps 3/31	GS(F)		Rare	c.100µm	Single Common	c.100µm c.5µm	None observed	-
Lower Yealm Steps 3/32	GS		Common	c.200µm	Single	c.100µm	Common	c.100µm.
Upper Yealm Steps 2/10	GS(Dn)		Moderate	c.200µm	Moderate Common	<100µm c.5µm	Rare	c.1mm
Yellowmead 2/44	G(F)		Common	c.500µm	Moderate	<25µm	Rare	c.1mm
Yes Tor Bottom 2/60	GS	Two small c.100µm areas with clusters of pale ovoid 5x10µm crystals.	Rare	c.1mm	Rare Common	<50µm c.5µm	Moderate	c.1mm

3.1.4: Compositional Analysis of Slags

3.1.4.1: Bulk Analysis of Slag

Bulk analysis of slags was carried out using scanning electron microscopy at 1000x magnification; data was collected from six points across the surface of each sample, avoiding prills and mineral inclusions whenever possible. The results, presented in Appendix 4 (but see also Appendix 13), show that slag composition within any particular sample is not uniform: slight variations exist that may be attributed to incomplete mixing of minerals from the ore during slag formation. It might be expected that low viscosity melts would be more uniform than high viscosity melts because any chemical species that were initially present in uneven concentrations would be more mobile within the melt, however there are no clear trends within the standard deviations of the results that would permit samples that seem from their morphologies to be highly viscous to be distinguished from those that are more fluid. This is likely to be an effect of scale (see p294).

From the mean composition of the samples (Table 3.2) it can be seen that all tin smelting slags are alumino-silicates, accompanied by a range of other elements that are present in lesser quantities: the most abundant of these are usually tin and iron, however some samples are also rich in titanium and tungsten. Relative percentages of each element are shown in Figures 3.11 to 3.29.

The amount of tin present varies markedly between samples, from under 5% up to 60%, but percentages of SnO can be linked to the technology by which the slag was produced only loosely. Thus, while it may be noted that SnO is generally more abundant in early slags and is low in some (but not all) of the reverberatory slags, there are blowing house

Table 3.2: Mean Chemical Composition of Slag Matrix (wt%)

Oxide	Avon Dam 2/20	Blackaller 4/22	Butterbrook 2/33	Butterbrook 2/34	Caerloggas 3/44	Caerloggas 3/45	Carvedras 3/30	Charlestown 4/20	Crift Farm 4/15	Crift Farm 4/16	Crift Farm 4/17	Crift Farm 4/27	Ditsworthy 3/01	Doe Tor Green 2/12	Drakeford Bridge 2/19	Eylesbarrow 2/35	Eylesbarrow 4/05	Eylesbarrow 4/06
Na_2O	2.7	3.5	2.3	1.8	1.4	1.6	1.9	1.3	2.7	2.4	2.3	2.4	1.6	2.4	2.0	2.6	1.4	1.6
MgO	3.7	3.7	3.3	2.5	2.0	2.4	1.0	1.1	3.7	4.3	3.4	3.3	1.7	3.4	1.3	1.2	0.9	0.4
Al_2O_3	16.7	21.1	16.0	14.1	14.0	15.7	24.9	14.5	18.1	20.2	23.9	19.9	13.8	15.6	11.0	22.1	29.8	27.6
SiO_2	43.1	42.4	37.5	35.5	25.3	28.6	52.7	37.2	41.2	41.5	39.6	41.3	34.5	41.2	31.1	49.5	60.2	54.2
P_2O_5	0.5	0.4	0.4	nd	nd	0.1	nd	0.1	0.0	nd	nd	0.1	0.1	0.3	0.2	0.1	0.0	nd
K_2O	1.9	2.7	1.3	1.9	0.8	0.9	2.2	1.7	1.6	1.4	1.3	1.3	2.6	1.5	3.2	3.7	2.8	1.3
CaO	1.2	2.4	0.8	0.9	0.8	0.7	1.3	1.0	1.0	1.2	0.9	1.1	2.0	0.7	2.2	2.8	0.4	0.6
TiO_2	8.0	2.8	6.1	7.7	1.6	1.8	2.0	2.4	2.6	2.2	2.3	2.8	6.0	7.7	10.4	1.9	1.8	0.8
V_2O_5	0.4	0.1	0.2	0.2	0.1	nd	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.0
MnO	0.5	0.3	0.5	0.7	0.5	0.5	0.3	0.1	0.4	0.4	0.3	0.1	0.4	0.8	0.7	0.1	0.1	0.1
FeO	9.3	14.4	13.5	23.4	5.3	5.3	7.3	26.0	8.0	5.9	6.8	8.6	8.4	11.0	26.1	13.1	4.3	6.9
CuO	0.1	0.0	0.0	nd	nd	0.0	0.0	0.0	0.0	nd	nd	0.0	0.0	nd	nd	0.0	0.0	0.1
ZnO	nd	0.1	nd	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	1.7	0.1	1.1	1.0	0.4	0.3	0.3	0.5	0.3	0.2	0.4	0.2	0.7	4.6	0.6	0.1	nd	nd
MoO_3	nd	0.1	0.1	0.3	0.2	0.1	0.2	1.0	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.0	0.1
SnO	11.0	8.3	17.0	7.6	44.5	37.5	6.6	13.0	19.4	19.8	17.4	19.1	28.3	10.8	10.6	3.9	0.0	6.6
Sb_2O_3	0.1	0.2	0.1	nd	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.2	0.1	0.0	0.0
WO_3	0.5	0.5	1.1	3.3	3.7	3.0	0.6	1.4	1.9	1.9	1.6	0.7	0.3	1.1	0.7	0.0	0.1	0.2
Sum	101.3	103.1	101.1	100.9	100.9	98.8	101.4	101.5	101.3	101.5	100.6	101.4	100.8	101.2	100.6	101.4	102.0	100.3

nd = not detected in the sample 0.0 = mean of individual analytical runs on the sample rounded to zero

Oxide	Glazebrook 2/58	Gobbett 2/28	Hurdon 2/01	Hurdon 4/26	Lether Tor Farm 2/11	Lingcombe 3/19	Lingcombe 3/20	Longstone 2/06	Longstone 2/07	Longstone 2/47	Longstone 4/24	Lustleigh 2/50	Lustleigh 2/51	L Merrivale 4/04	L Merrivale 4/28
Na_2O	1.9	2.0	1.1	1.0	1.9	2.5	2.1	2.0	1.9	2.2	1.8	1.6	1.8	1.7	2.3
MgO	3.0	2.9	2.5	1.4	4.2	3.4	1.3	3.4	3.1	3.5	2.5	1.4	1.7	2.6	2.7
Al_2O_3	17.7	13.2	10.5	10.9	14.5	17.7	11.1	14.6	14.0	19.1	13.0	12.6	11.6	18.2	17.9
SiO_2	37.5	35.8	29.2	30.8	38.7	42.0	37.2	37.1	35.6	42.7	34.3	29.2	28.5	39.7	43.6
P_2O_5	0.1	0.2	nd	nd	0.4	1.1	0.0	0.2	0.2	0.7	0.4	0.2	0.4	0.6	0.2
K_2O	1.3	1.3	1.5	1.3	1.6	2.8	2.8	1.4	1.2	1.4	1.0	2.5	2.1	1.3	0.9
CaO	1.0	0.7	2.3	0.6	0.4	2.0	1.9	0.7	0.5	1.5	0.5	2.5	2.2	0.9	0.6
TiO_2	6.6	6.8	4.8	3.6	4.6	7.0	8.8	2.8	2.6	2.0	4.3	10.6	8.9	2.7	2.2
V_2O_5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.2	0.1
MnO	0.6	0.5	2.2	3.0	0.4	0.5	1.0	0.3	0.2	0.2	0.3	2.0	3.6	1.0	0.2
FeO	17.3	15.7	9.8	7.9	8.9	14.4	24.4	7.4	6.8	16.7	6.8	25.9	26.2	20.9	14.4
CuO	nd	0.0	0.0	nd	0.0	0.0	nd	0.0	nd	0.0	0.0	0.0	0.0	nd	0.0
ZnO	0.0	0.0	0.0	0.1	0.1	0.1	0.1	nd	0.1	0.0	0.0	0.0	0.0	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.7	0.6	2.1	2.4	0.5	0.1	1.2	0.9	0.8	0.0	0.2	0.2	0.1	0.1	0.2
MoO_3	0.2	0.1	1.0	1.3	0.1	0.1	0.1	nd	0.1	0.0	0.1	0.1	0.0	0.1	0.1
SnO	10.1	20.2	20.0	22.8	25.1	7.1	8.4	29.9	30.9	11.0	35.3	11.3	12.8	10.1	16.7
Sb_2O_3	0.0	0.1	0.4	0.2	nd	0.1	0.1	0.2	0.4	0.1	0.1	0.1	0.3	0.1	0.1
WO_3	2.5	0.7	15.0	15.6	0.5	0.3	0.5	0.3	0.5	0.2	0.1	0.6	0.4	0.9	0.7
Sum	100.9	100.8	102.4	102.9	102.0	101.2	100.9	101.1	98.8	101.3	101.0	100.7	100.6	101.0	102.9

Oxide	U Merrivale 2/21	U Merrivale 2/22	U Merrivale 2/23	U Merrivale 2/24	U Merrivale 2/25	U Merrivale 2/26	U Merrivale 2/27	U Merrivale 2/31	U Merrivale 2/32	U Merrivale 2/52	U Merrivale 2/53	U Merrivale 2/54	U Merrivale 2/55	U Merrivale 2/56	U Merrivale 2/57	U Merrivale 3/24	U Merrivale 3/27
Na_2O	3.9	1.3	2.3	1.6	1.2	1.4	0.4	2.8	1.5	2.1	3.4	2.5	1.5	2.0	1.9	2.0	1.0
MgO	3.3	2.4	4.1	2.6	1.5	3.5	1.0	3.9	2.4	3.8	4.3	3.0	2.9	2.0	3.3	3.0	1.5
Al_2O_3	19.5	12.3	14.8	13.0	9.4	17.5	8.1	20.9	12.0	16.2	17.9	11.5	10.9	11.7	15.6	15.2	10.2
SiO_2	45.3	38.1	42.1	36.5	25.1	36.9	22.7	45.6	30.5	41.7	48.2	34.5	31.0	36.7	39.4	39.9	28.6
P_2O_5	nd	0.3	0.2	0.1	0.0	0.3	nd	0.5	0.1	0.0	0.2	0.5	0.0	nd	0.1	0.0	0.1
K_2O	2.1	1.2	1.9	0.9	0.9	1.1	0.8	0.8	0.7	1.1	1.5	1.1	1.0	1.1	1.1	1.6	1.3
CaO	1.0	0.7	0.8	1.0	0.7	0.7	0.3	0.5	0.5	0.5	0.8	0.7	1.0	0.3	1.0	0.6	0.9
TiO_2	5.1	13.5	6.6	3.0	6.4	3.0	2.2	1.6	14.8	6.5	3.0	7.6	6.7	12.7	7.0	5.4	4.1
V_2O_5	0.2	0.3	0.1	0.1	0.2	0.2	0.2	0.1	0.3	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1
MnO	0.6	1.2	1.4	4.1	0.5	0.4	1.7	0.2	1.4	0.8	0.7	0.8	1.2	1.0	2.5	1.0	2.6
FeO	7.5	16.6	11.2	12.8	9.7	19.4	35.1	12.6	14.5	9.1	12.7	11.4	16.2	11.6	10.9	10.9	36.8
CuO	nd	0.0	0.0	0.0	0.0	nd	nd	nd	0.0	nd	nd	0.0	0.1	0.0	0.0	nd	0.0
ZnO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	nd	0.1	nd	0.0	0.0	0.0	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	0.1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	2.0	0.3	3.9	0.3	1.9	0.3	2.0	0.1	4.3	3.2	0.2	10.3	3.1	1.3	2.4	1.5	0.7
MoO_3	0.3	0.0	0.1	0.1	0.1	0.3	1.2	0.2	0.1	0.3	0.1	0.2	0.3	0.4	0.2	0.2	0.2
SnO	10.6	11.3	9.5	22.6	41.1	14.4	16.5	11.0	15.3	14.2	7.9	15.8	21.7	18.8	11.7	15.8	10.2
Sb_2O_3	0.1	0.1	0.2	0.3	0.4	0.1	0.0	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.1	0.0	0.0
WO_3	0.9	1.4	2.0	0.9	1.6	1.6	10.1	0.7	2.3	1.3	0.5	1.1	3.1	1.3	3.8	3.9	2.3
Sum	102.4	100.9	101.2	100.1	100.8	101.0	102.0	101.5	100.8	101.0	101.5	101.1	100.8	101.1	101.0	101.0	100.7

Oxide	Metherel 2/48	Metherel 2/49	Nosworthy 3/16	Nosworthy 3/17	Outer Down 4/18	Retallack 4/01	Retallack 4/02	Retallack 4/03	Riddon 2/38	Riddon 2/39	South Hill I 2/42	South Hill I 2/43	South Hill II 2/17	Stannon Brook 2/02	Stannon Brook 2/03	Stannon Brook 2/04	Stannon Brook 4/25	Taw River 2/15	Taw River 2/40	Taw River 2/41	Teignhead Farm 2/14
Na_2O	1.0	1.2	1.7	1.2	2.5	1.8	1.6	1.5	1.8	1.5	1.9	2.0	1.6	1.6	1.5	2.3	2.2	1.5	1.5	2.0	2.2
MgO	1.2	1.0	2.9	2.3	1.1	1.7	1.4	1.3	2.9	2.8	2.0	2.9	2.2	2.6	3.6	3.2	3.3	2.8	3.0	5.0	2.7
Al_2O_3	10.2	6.8	11.7	9.9	14.1	14.5	13.2	12.2	13.2	13.6	11.8	14.8	12.7	12.8	12.6	14.4	15.0	9.5	9.7	14.4	12.1
SiO_2	20.8	19.6	31.4	27.0	40.2	36.3	41.5	34.9	41.5	41.7	35.9	42.5	35.4	40.9	42.7	44.4	48.5	23.6	29.6	40.2	35.6
P_2O_5	0.0	0.0	0.4	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.1	0.1	nd	nd	0.2	0.3
K_2O	1.5	0.9	1.4	1.5	4.2	3.8	3.2	3.5	1.6	1.8	2.7	2.3	1.9	2.3	1.8	2.1	1.1	0.7	1.1	1.5	2.2
CaO	1.4	0.4	1.0	1.0	1.4	3.9	4.3	3.6	0.7	0.8	1.8	1.1	0.8	1.1	0.8	0.9	0.9	0.6	0.8	1.1	1.5
TiO_2	2.2	1.0	10.9	11.8	9.6	1.0	1.0	0.5	5.0	5.6	13.0	8.9	11.1	10.7	4.5	9.2	2.0	9.2	8.4	9.2	13.3
V_2O_5	0.0	nd	0.3	0.3	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.2	0.3	0.1	0.2	0.1	0.1	0.2	0.2	0.2
MnO	2.3	0.5	1.3	1.6	0.5	0.4	0.5	0.4	0.5	0.5	0.9	1.1	0.7	0.9	0.4	0.7	0.5	1.2	1.6	1.3	0.9
FeO	10.0	10.8	19.7	23.3	17.6	12.2	12.5	7.8	21.0	19.8	20.6	16.1	20.8	20.2	22.8	15.9	14.7	11.2	12.1	12.9	18.6
CuO	nd	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	nd	nd	0.0	nd	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ZnO	0.0	0.1	0.0	nd	0.0	0.1	0.2	0.1	0.1	0.0	nd	0.0	0.1	0.1	nd	nd	0.1	0.0	0.0	nd	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.2	0.1	2.1	1.8	0.5	0.2	0.2	0.2	0.2	0.4	0.6	0.9	0.3	0.1	0.1	0.2	0.3	3.3	4.5	2.6	0.3
MoO_3	0.2	0.1	0.1	nd	0.0	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.2	0.4	0.7	0.1	0.1
SnO	54.8	60.2	16.5	17.4	10.8	22.4	17.5	32.2	11.6	11.9	8.1	6.6	12.2	6.9	9.9	7.6	9.2	31.1	19.4	8.5	10.3
Sb_2O_3	0.0	nd	0.2	0.2	0.1	0.3	0.2	0.1	0.1	0.1	0.2	nd	0.1	0.1	0.1	nd	0.1	0.3	0.2	0.0	0.1
WO_3	0.3	0.0	1.2	1.4	0.4	1.6	1.4	0.8	0.4	0.1	0.7	1.2	0.8	0.1	0.1	0.2	0.2	6.5	9.5	2.2	0.6
Sum	106.0	102.4	102.8	100.9	103.1	100.6	99.0	99.5	101.0	100.9	100.9	100.9	100.9	100.8	101.1	101.3	98.6	102.1	102.1	101.3	100.8

Oxide	Thornworthy 2/45	Thornworthy 2/46	Trereife (Stable Hobba) 3/35	Trereife (Stable Hobba) 3/36	Trereife (Stable Hobba) 4/21	Trevellas Porth, St Agnes 4/19	Wallabrook 3/18	Wapsworthy Newtake 2/29	Week Ford 4/23	Weir Quay 2/18	Whitten Knowles 2/36	Lower Yealm Steps 2/13	Lower Yealm Steps 3/31	Lower Yealm Steps 3/32	Upper Yealm Steps 2/10	Yellowmead 2/44	Yes Tor Bottom 2/60
Na_2O	2.0	0.8	0.5	0.3	0.8	1.6	2.4	1.6	3.1	1.3	1.4	0.7	2.4	2.2	1.2	2.5	2.1
MgO	1.7	0.6	0.2	0.2	0.9	2.1	4.3	2.5	4.7	1.0	2.7	0.9	2.2	3.2	1.7	3.7	2.8
Al_2O_3	12.2	7.1	10.7	9.4	13.9	15.6	14.4	11.9	18.4	14.5	12.2	7.8	13.9	16.5	10.7	18.0	15.9
SiO_2	34.2	26.3	28.1	25.0	32.3	35.0	39.2	36.2	44.4	34.5	34.8	19.6	35.0	40.1	31.2	42.0	39.5
P_2O_5	0.3	0.0	nd	nd	nd	0.5	0.3	0.3	0.5	0.2	0.4	0.0	0.0	0.1	nd	0.7	0.4
K_2O	3.7	1.5	1.2	1.3	1.7	4.0	1.2	0.7	1.5	2.5	1.1	0.5	1.1	1.6	1.7	3.3	1.6
CaO	3.4	0.8	1.7	1.6	1.4	3.5	0.8	1.0	0.7	1.6	0.5	0.5	0.6	0.9	2.4	1.4	0.5
TiO_2	12.3	11.0	1.4	1.5	3.3	1.9	10.4	8.7	6.0	2.2	2.8	1.0	4.9	3.3	5.4	5.7	4.4
V_2O_5	0.2	0.2	0.0	0.0	0.0	0.0	0.3	0.3	0.2	0.0	0.1	0.0	0.3	0.1	0.1	0.1	0.3
MnO	1.0	1.0	0.4	0.4	0.4	1.3	0.8	2.5	0.4	0.1	0.2	0.2	0.4	0.3	1.2	1.8	0.4
FeO	23.4	34.2	27.0	29.4	27.4	17.3	18.8	11.8	12.1	20.9	11.1	36.2	7.1	6.8	15.1	9.0	11.7
CuO	nd	nd	0.0	0.0	0.0	0.1	0.0	nd	nd	0.0	0.0	nd	0.0	0.1	0.0	0.0	nd
ZnO	0.0	0.0	0.1	0.0	0.1	0.0	nd	0.1	0.0	0.1	0.1	0.1	nd	0.0	0.0	0.1	nd
As_2O_3	nd	nd	0.0	0.1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.2	0.6	1.9	2.0	1.1	0.4	0.6	0.1	3.6	0.6	0.2	0.3	0.7	0.8	1.8	1.2	1.5
MoO_3	0.0	0.0	3.2	3.1	0.5	0.2	0.1	0.0	0.0	0.5	0.1	0.1	0.2	0.3	1.0	0.1	0.0
SnO	5.8	18.4	14.8	13.7	12.8	15.6	6.5	23.3	8.2	18.4	32.9	31.6	30.3	23.3	18.6	11.6	19.9
Sb_2O_3	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.0	0.1	0.0	0.1	0.3	0.2	0.1	0.1	0.1	0.1
WO_3	0.4	0.6	10.5	13.0	5.0	1.7	0.3	0.3	0.4	2.4	0.3	0.7	1.9	1.9	10.9	0.4	0.4
Sum	100.7	103.1	101.9	101.0	101.5	100.9	100.5	101.0	104.1	100.8	101.0	100.5	101.0	101.4	102.8	101.5	101.1

Figure 3.11: Na_2O content of Archaeological Tin Slags (wt%)

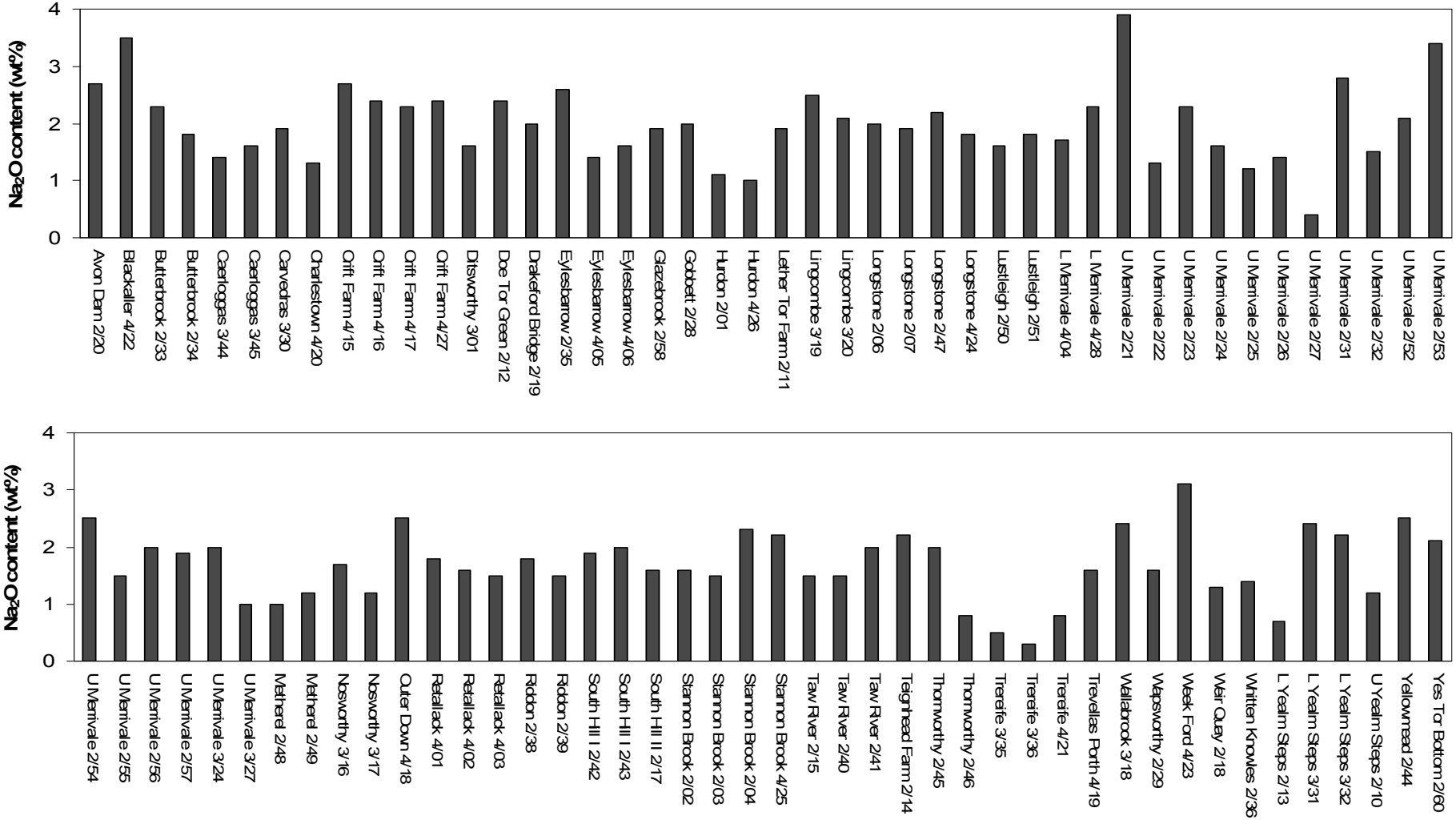


Figure 3.12: MgO content of Archaeological Tin Slags (wt%)

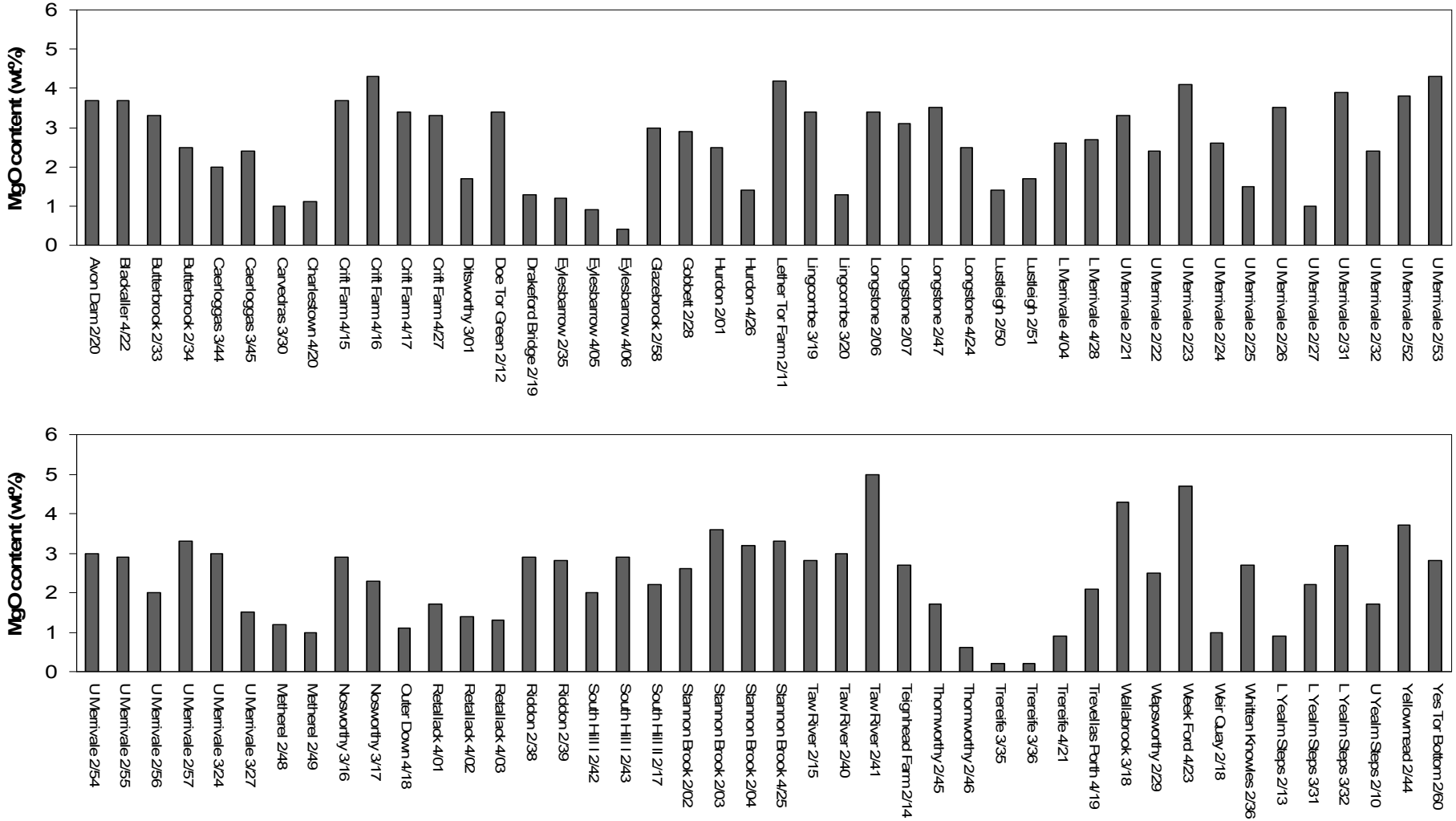


Figure 3.13: Al_2O_3 content of Archaeological Tin Slags (wt%)

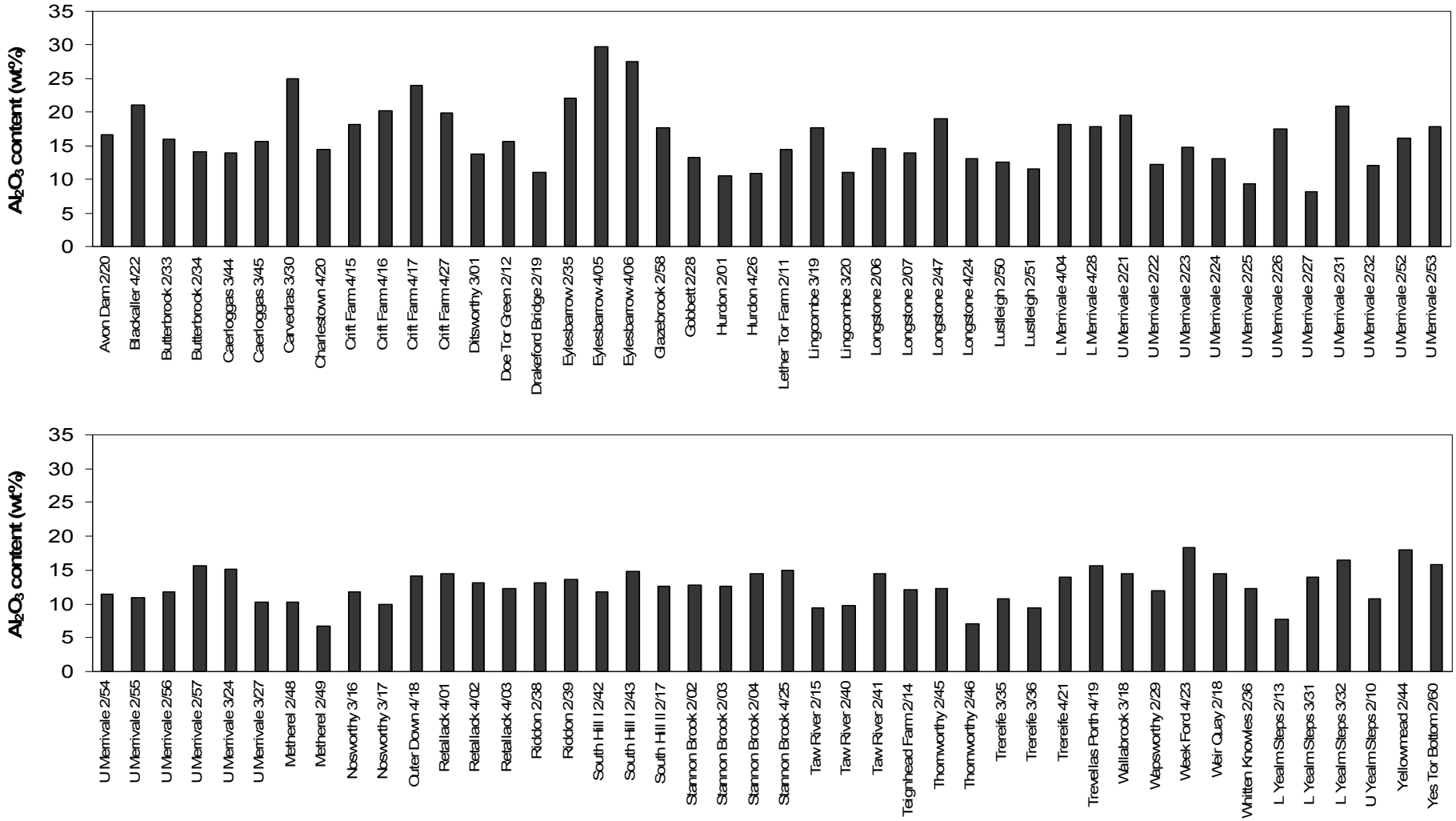


Figure 3.14: SiO_2 content of Archaeological Tin Slags (wt%)

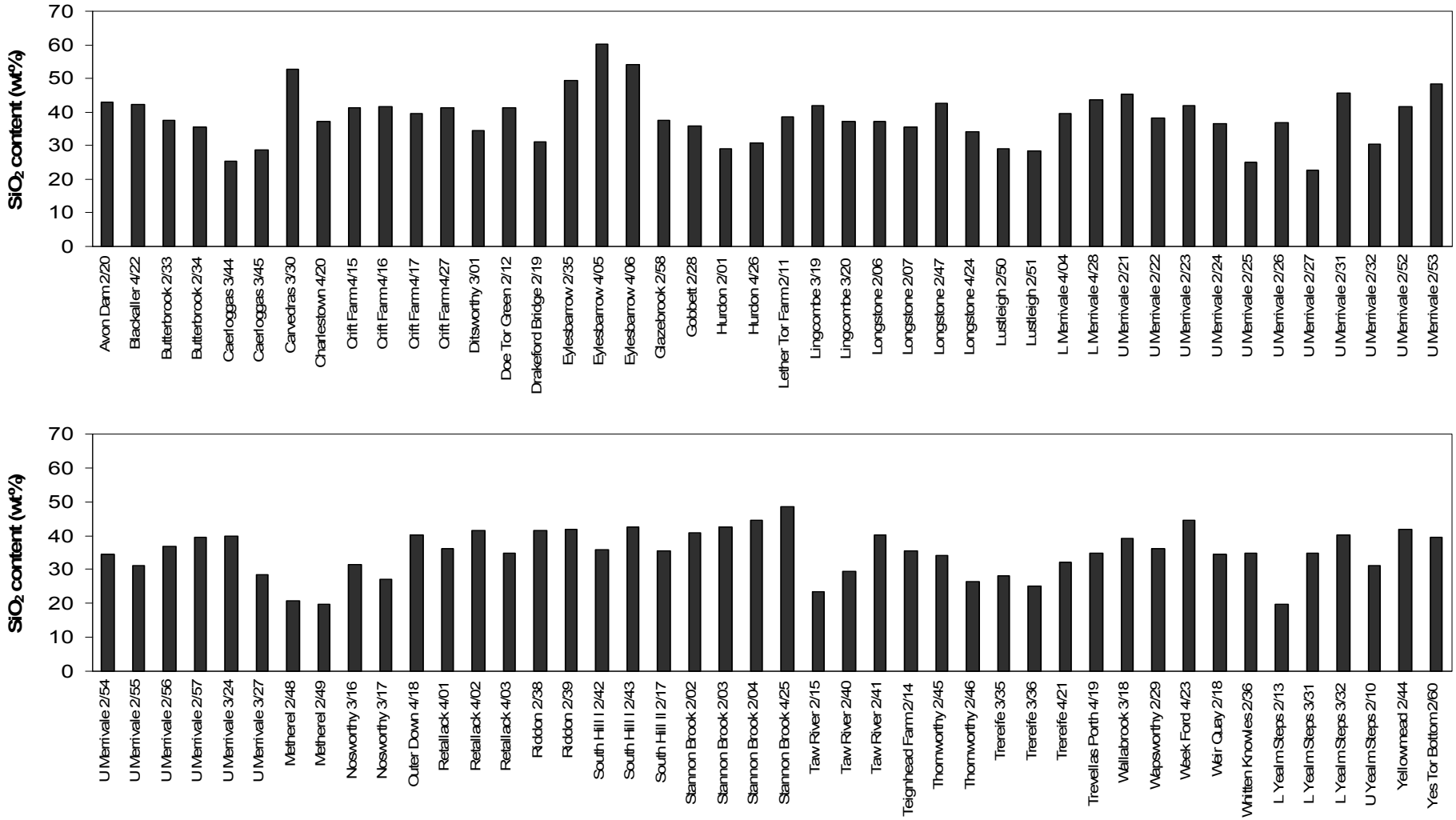


Figure 3.15: P_2O_5 content of Archaeological Tin Slags (wt%)

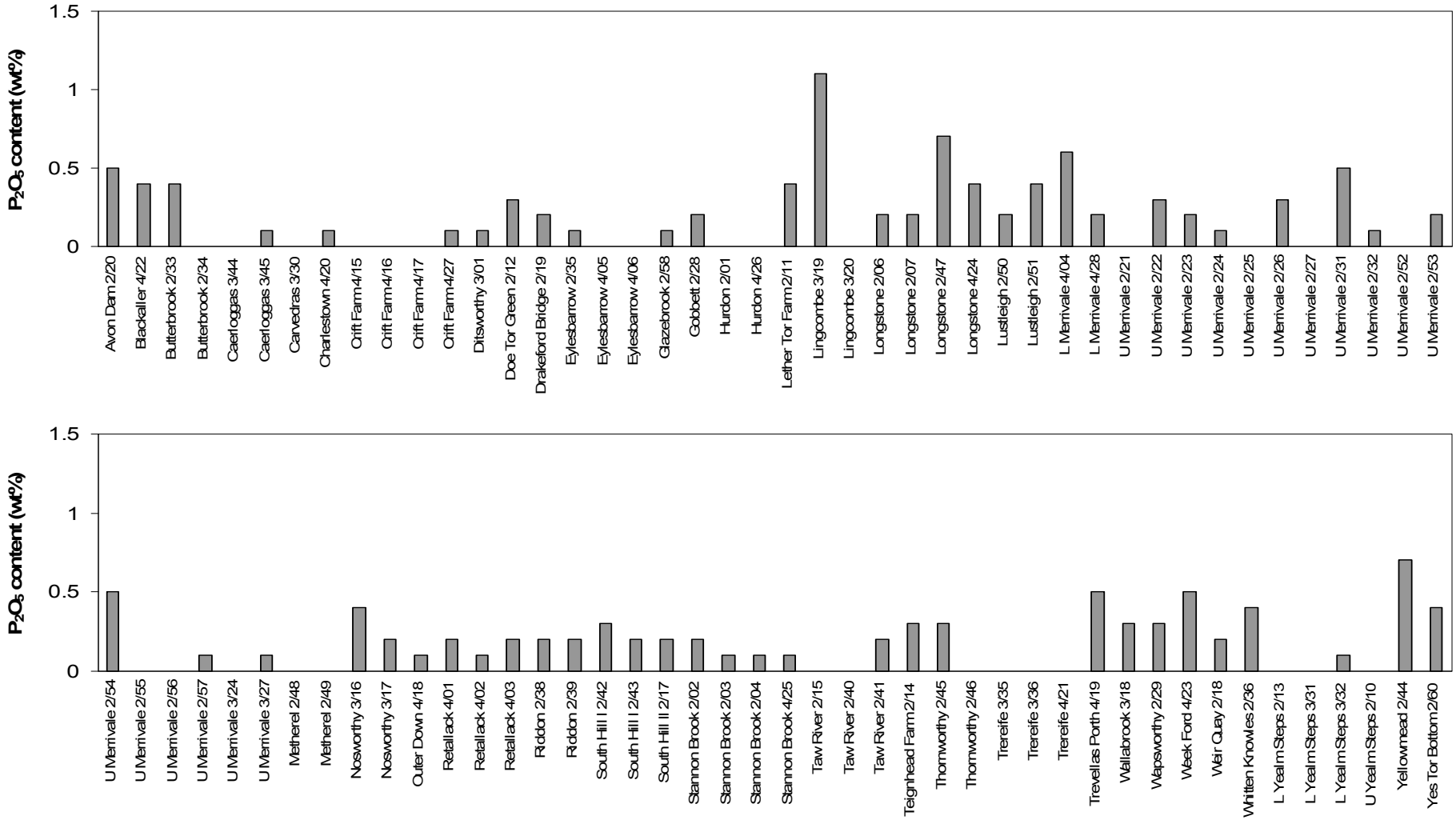


Figure 3.16: K_2O content of Archaeological Tin Slags (wt%)

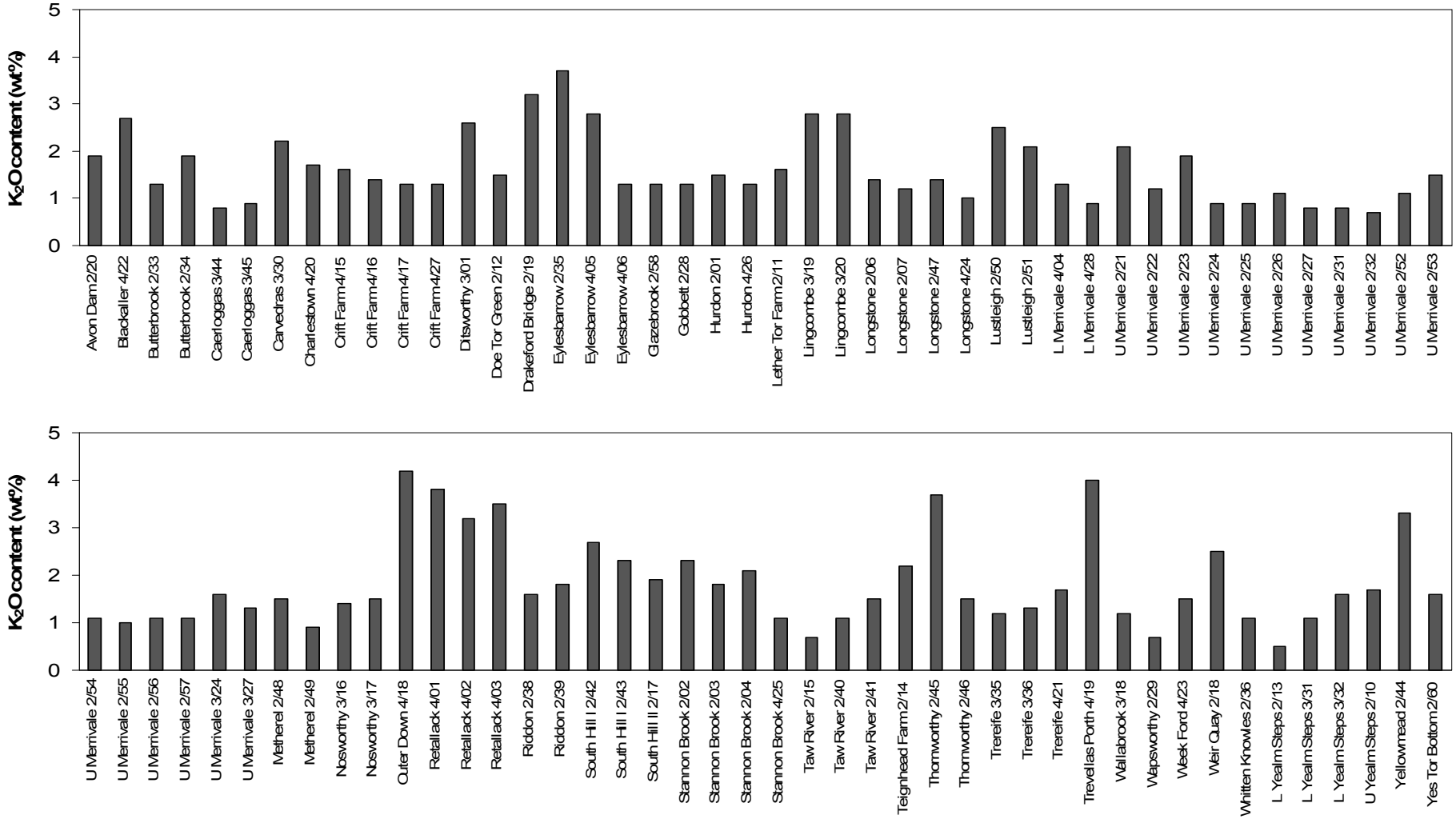


Figure 3.17: CaO content of Archaeological Tin Slags (wt%)

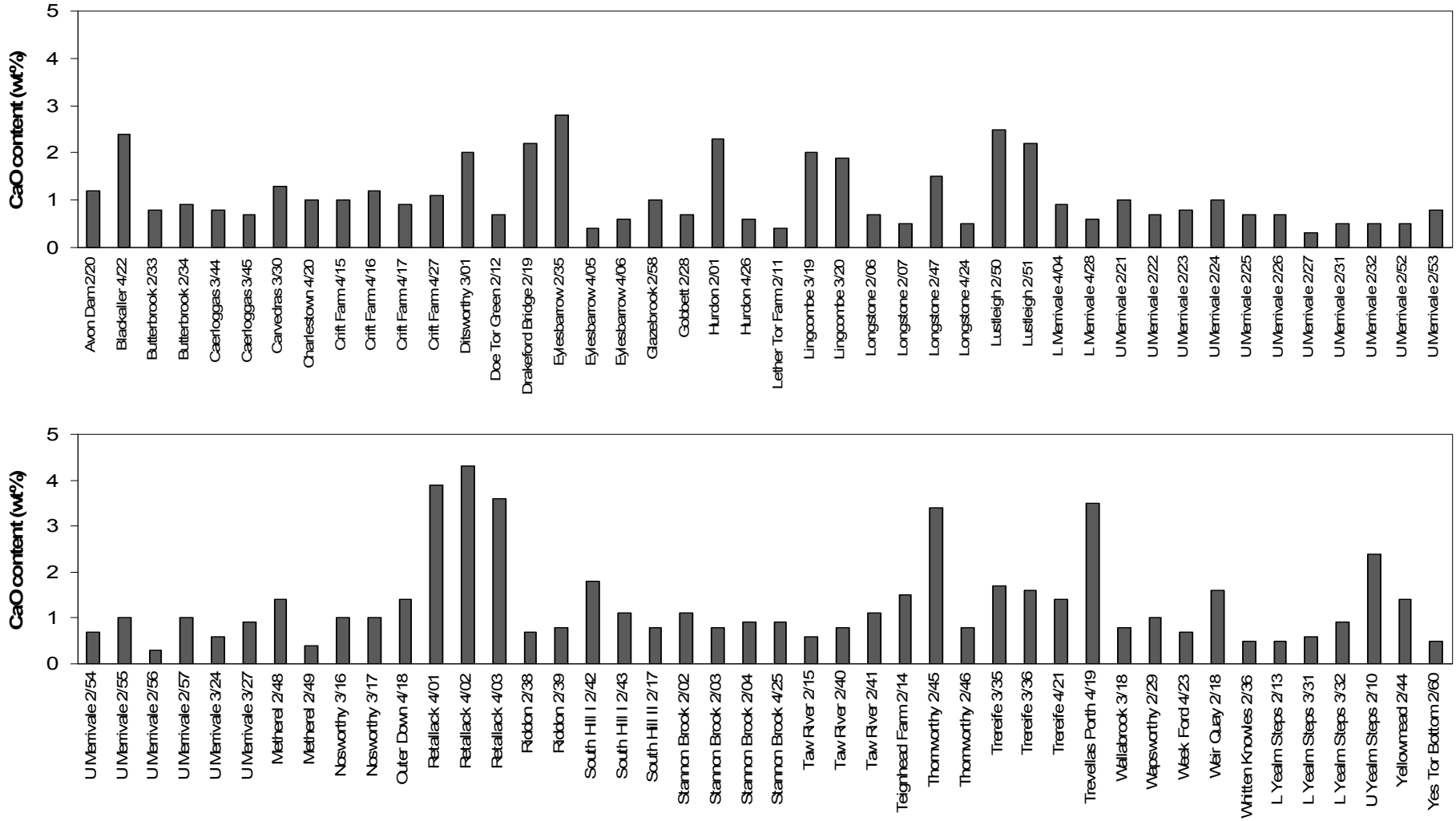


Figure 3.18: TiO_2 content of Archaeological Tin Slags (wt%)

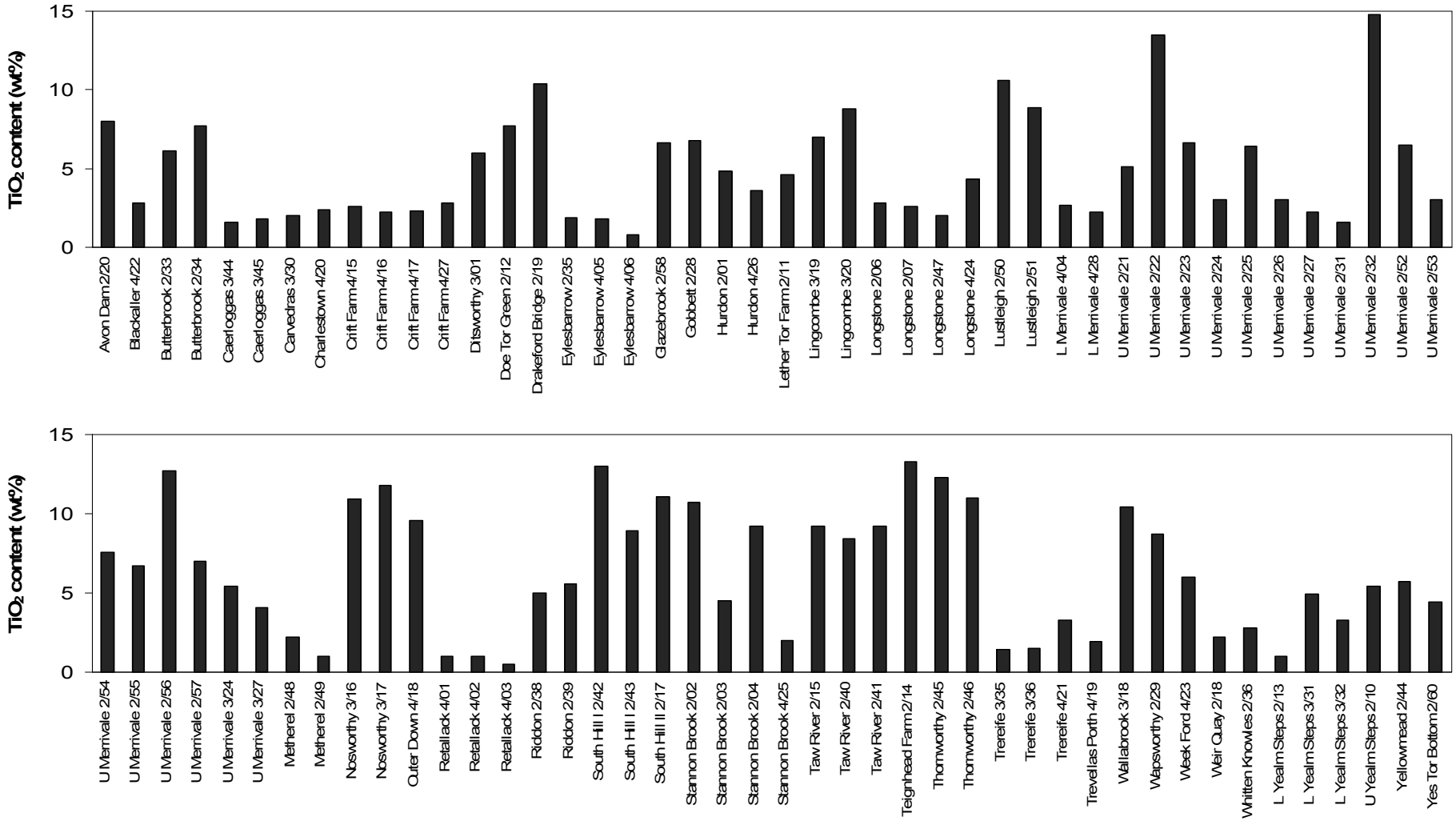


Figure 3.19: V_2O_5 content of Archaeological Tin Slags (wt%)

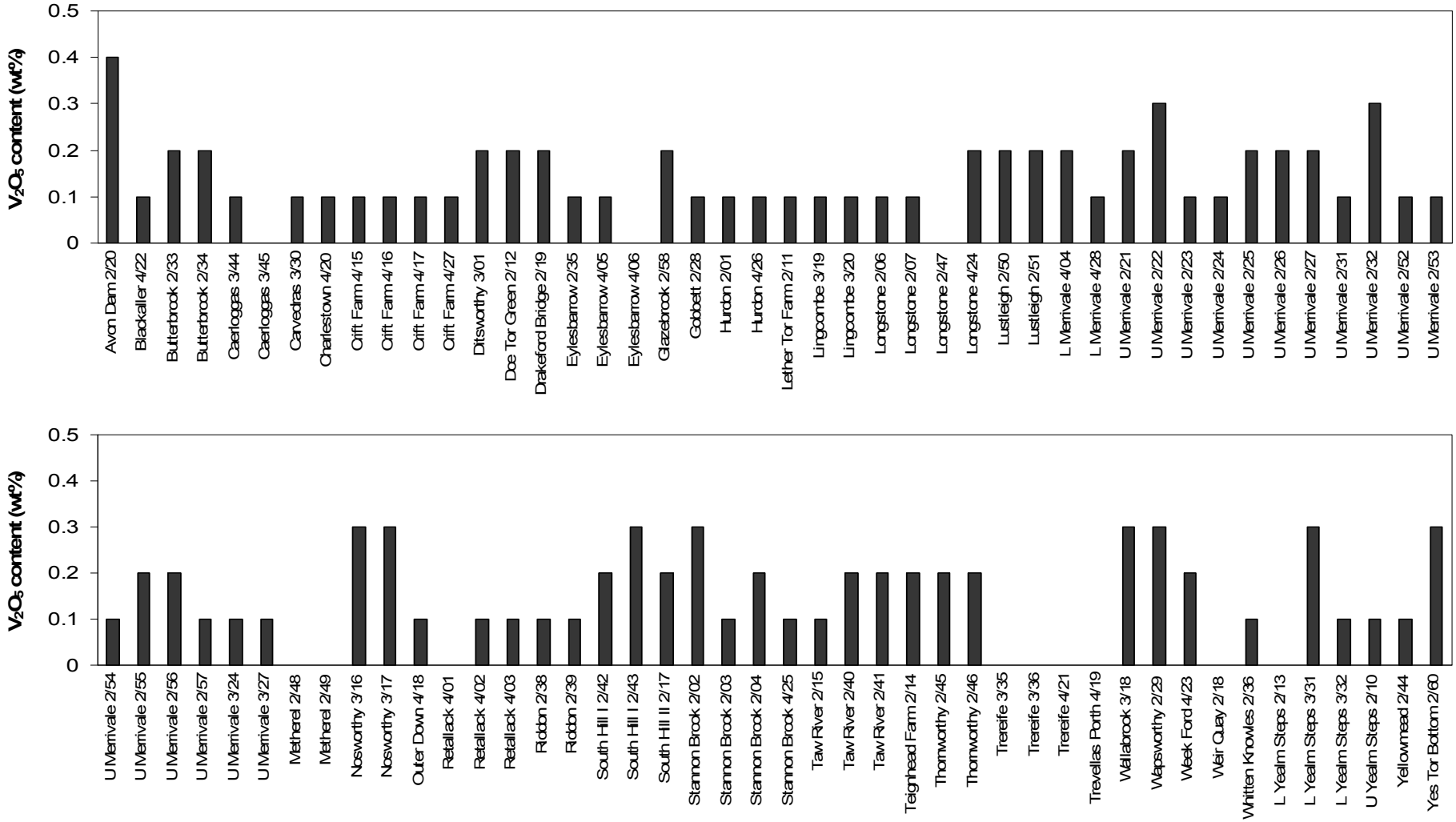


Figure 3.20: MnO content of Archaeological Tin Slags (wt%)

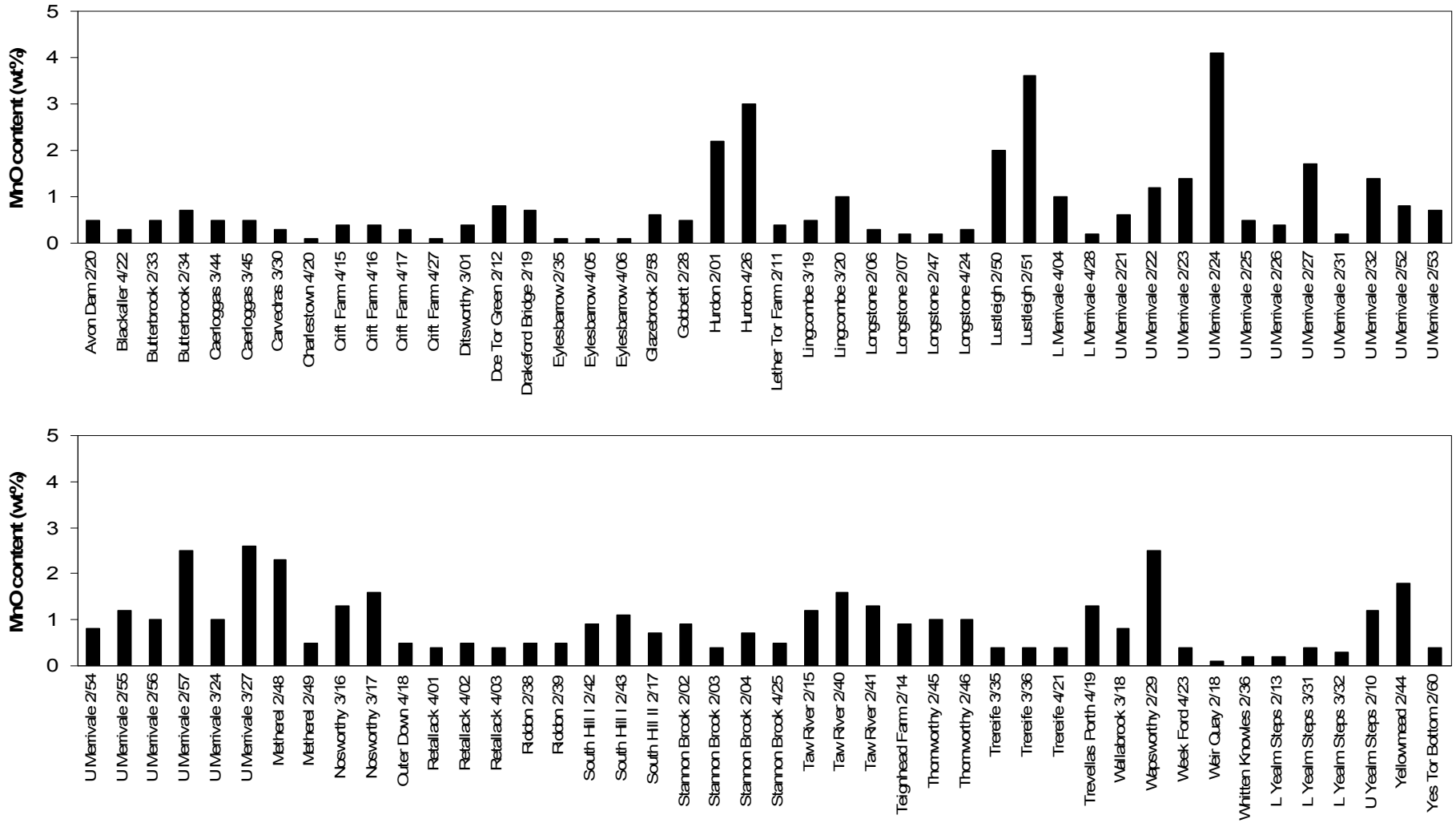


Figure 3.21: FeO content of Archaeological Tin Slags (wt%)

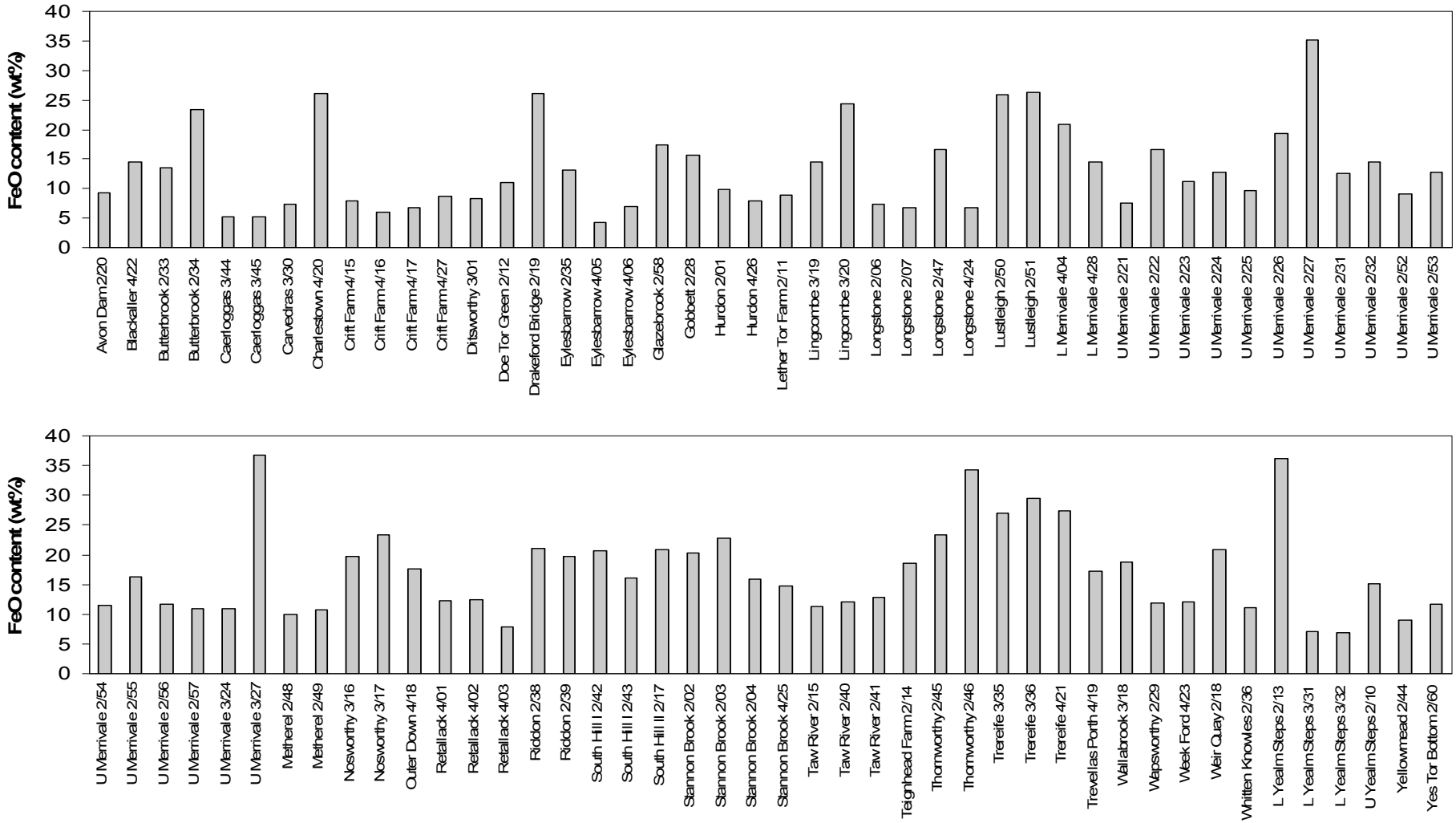


Figure 3.22: CuO content of Archaeological Tin Slags (wt%)

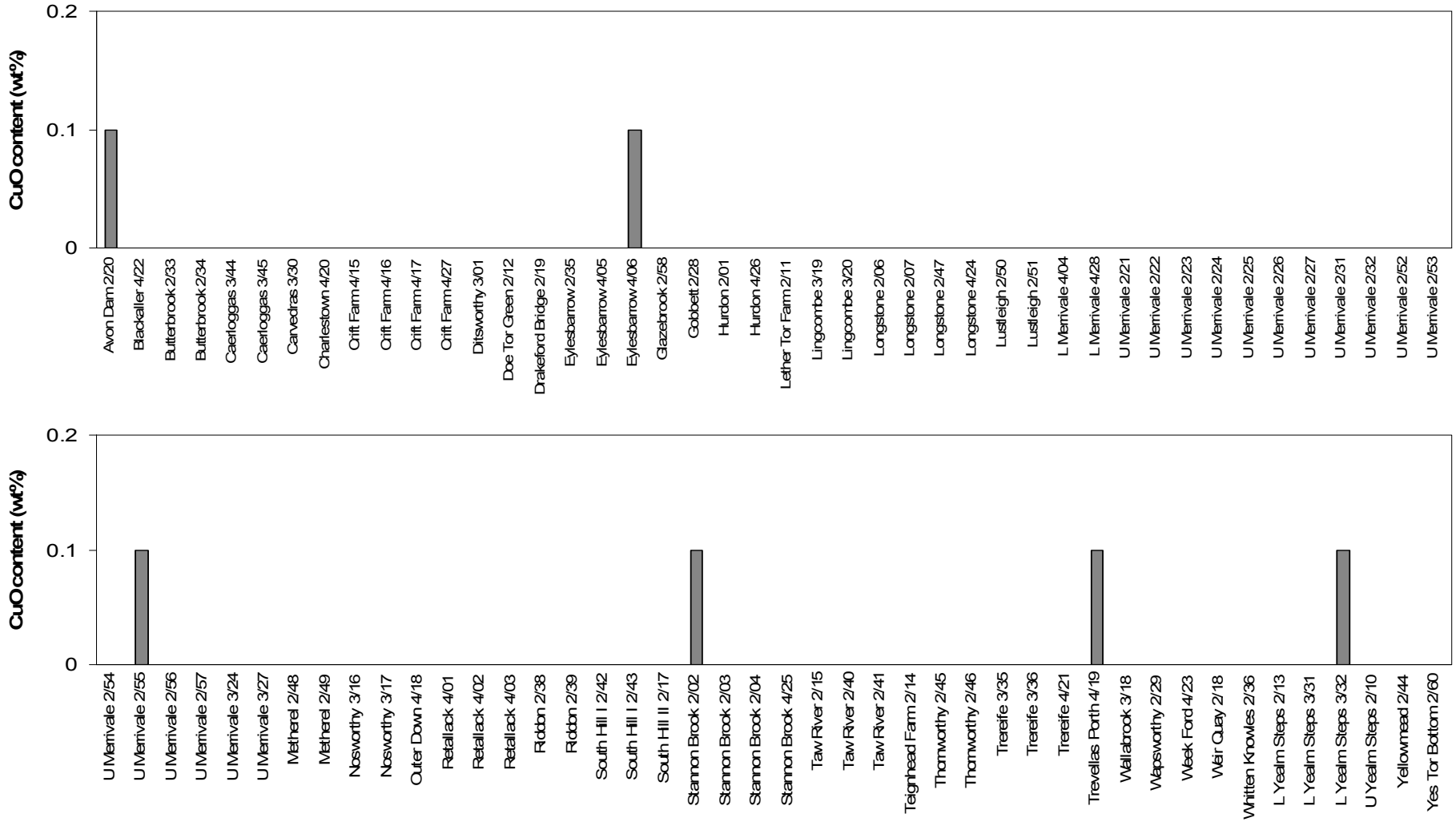


Figure 3.23: ZnO content of Archaeological Tin Slags (wt%)

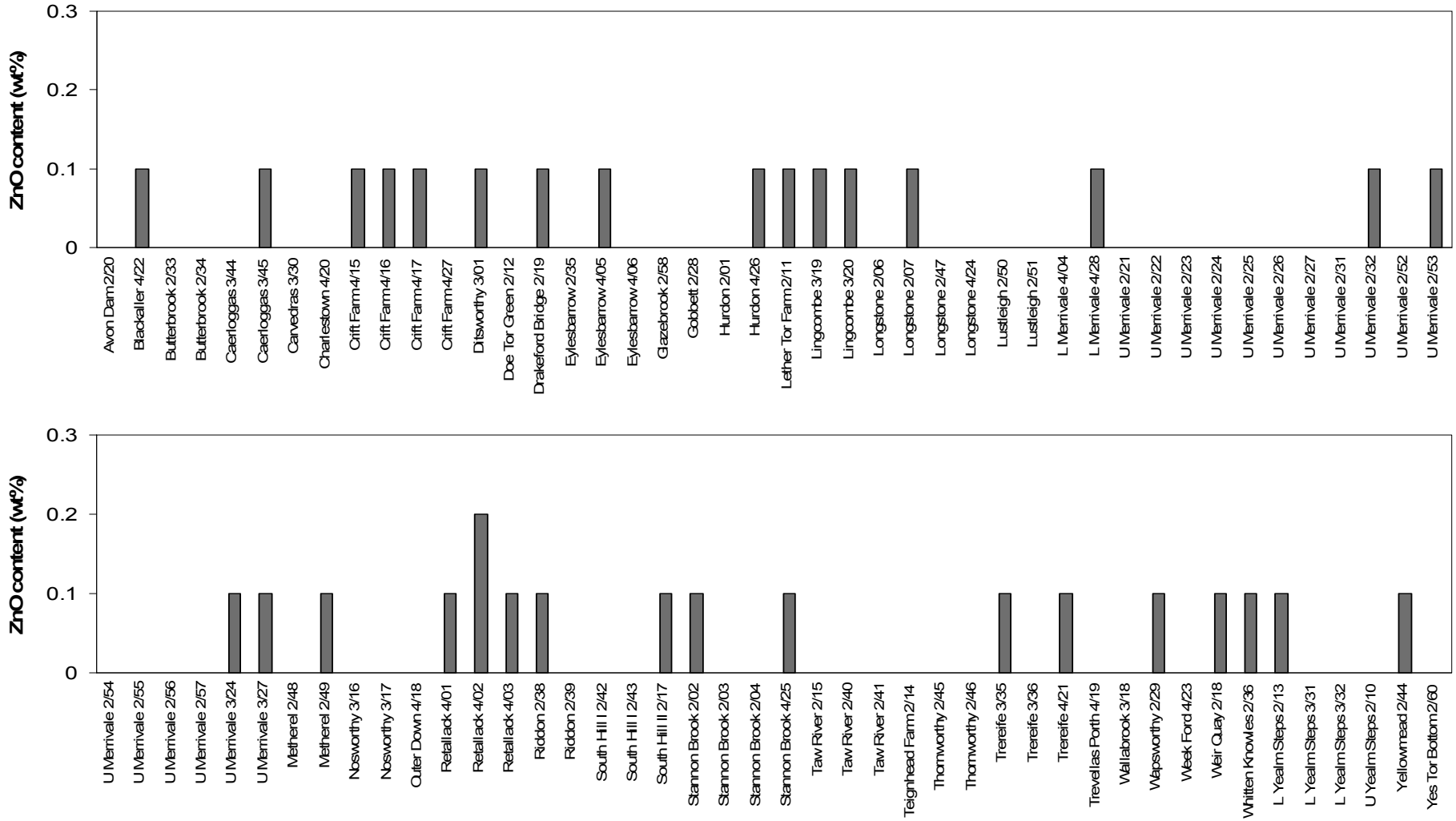


Figure 3.24: As_2O_3 content of Archaeological Tin Slags (wt%)

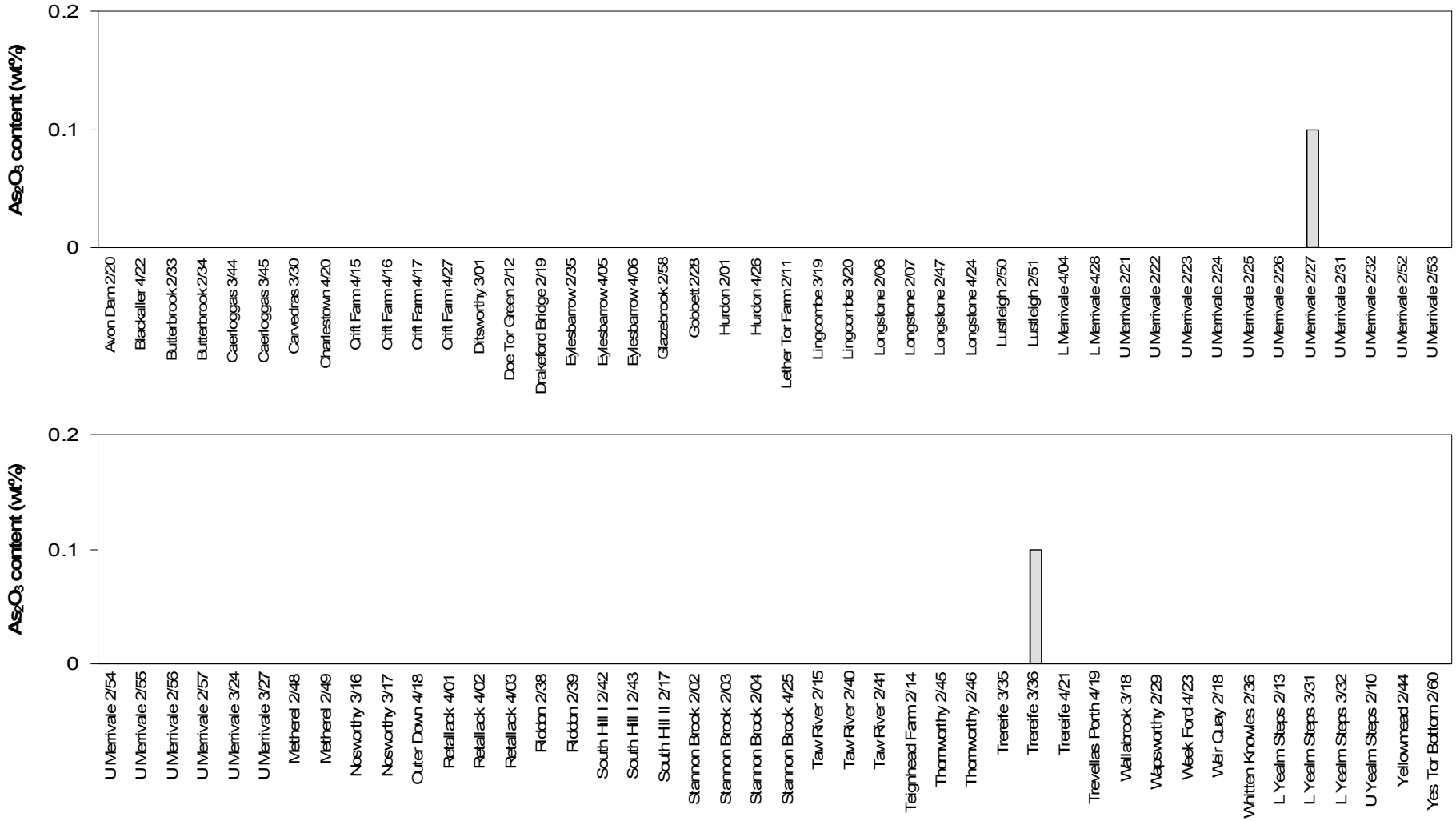


Figure 3.25: ZrO_2 content of Archaeological Tin Slags (wt%)

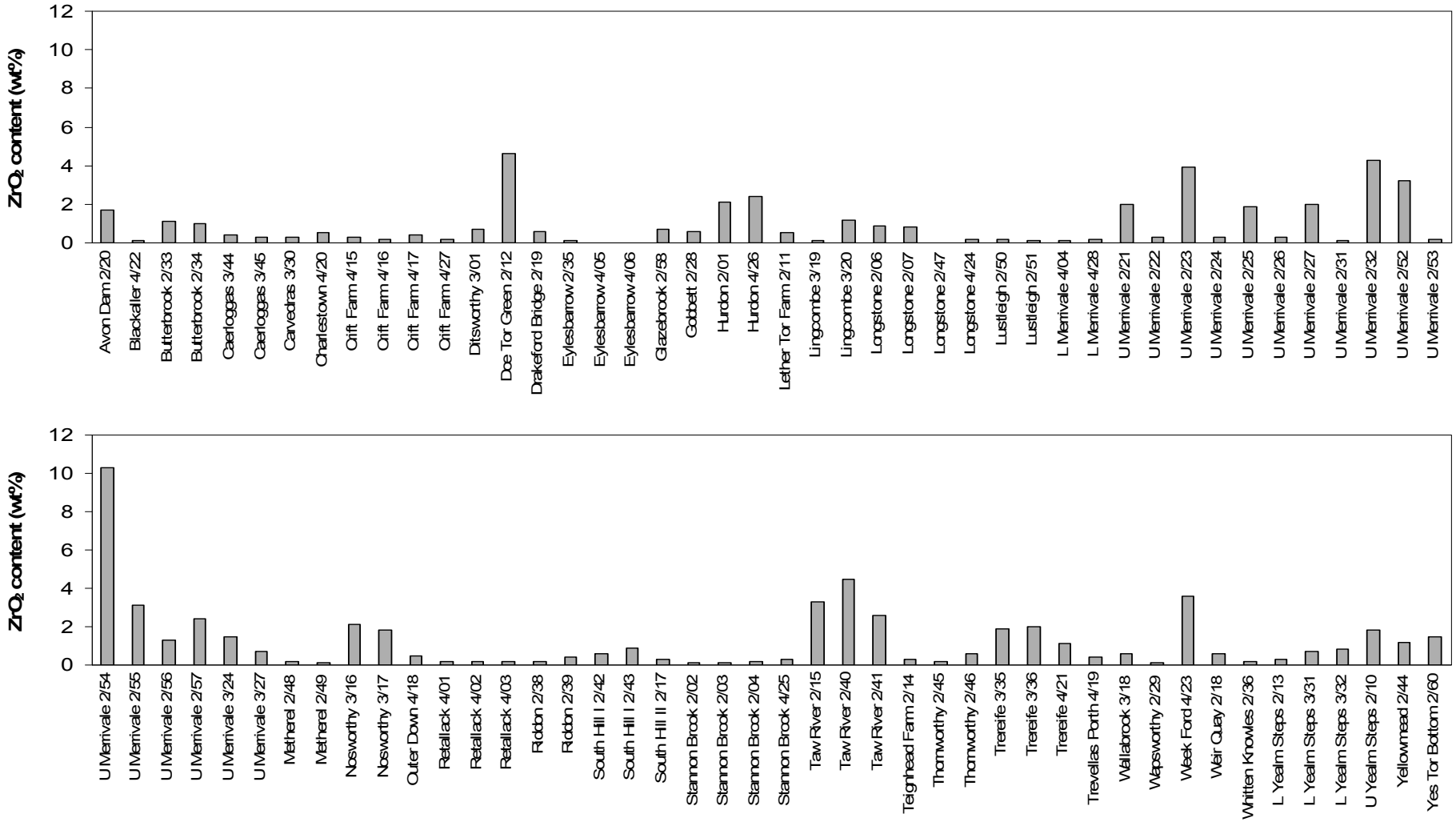


Figure 3.26: MoO_3 content of Archaeological Tin Slags (wt%)

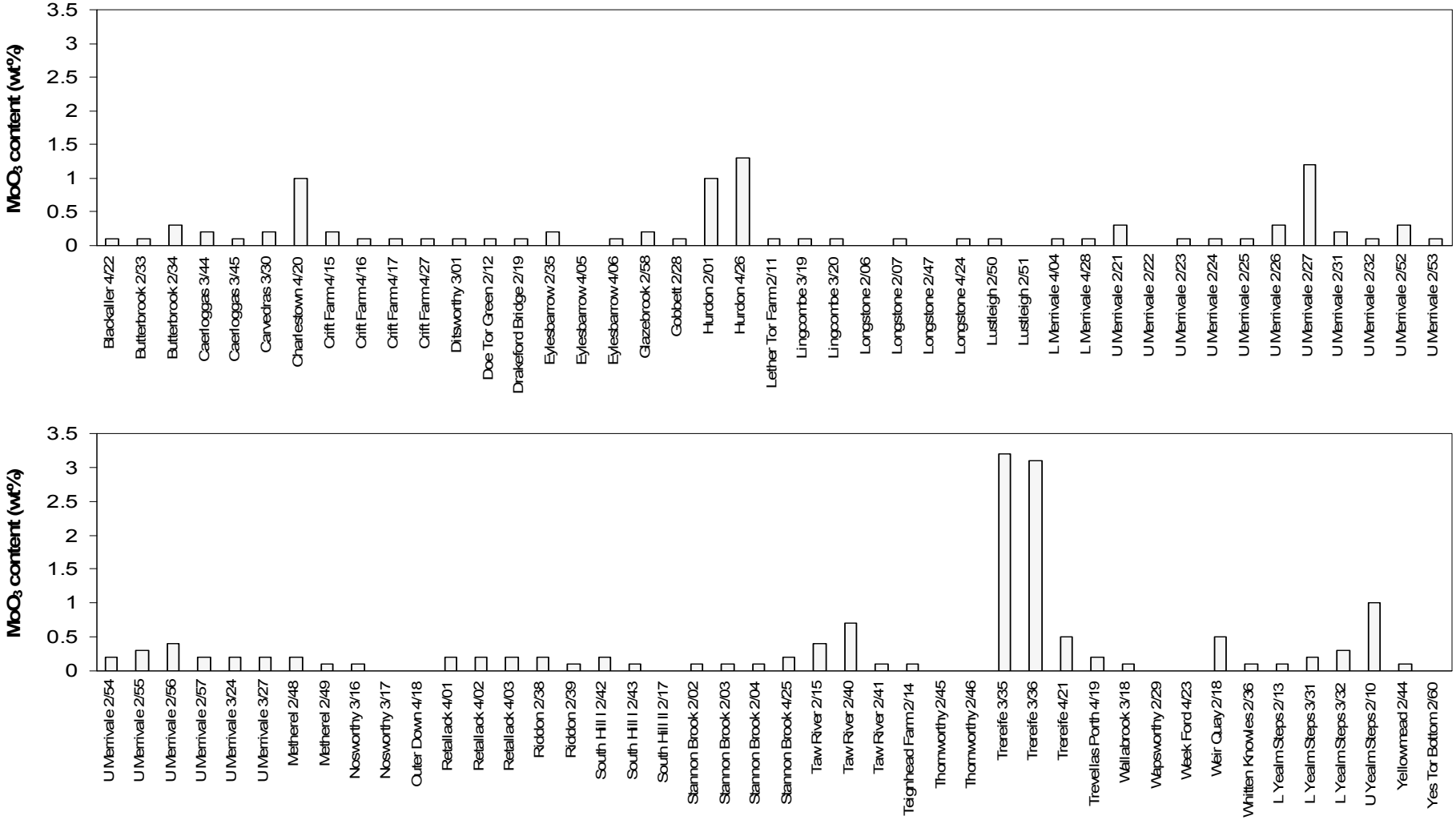


Figure 3.27: SnO content of Archaeological Tin Slags (wt%)

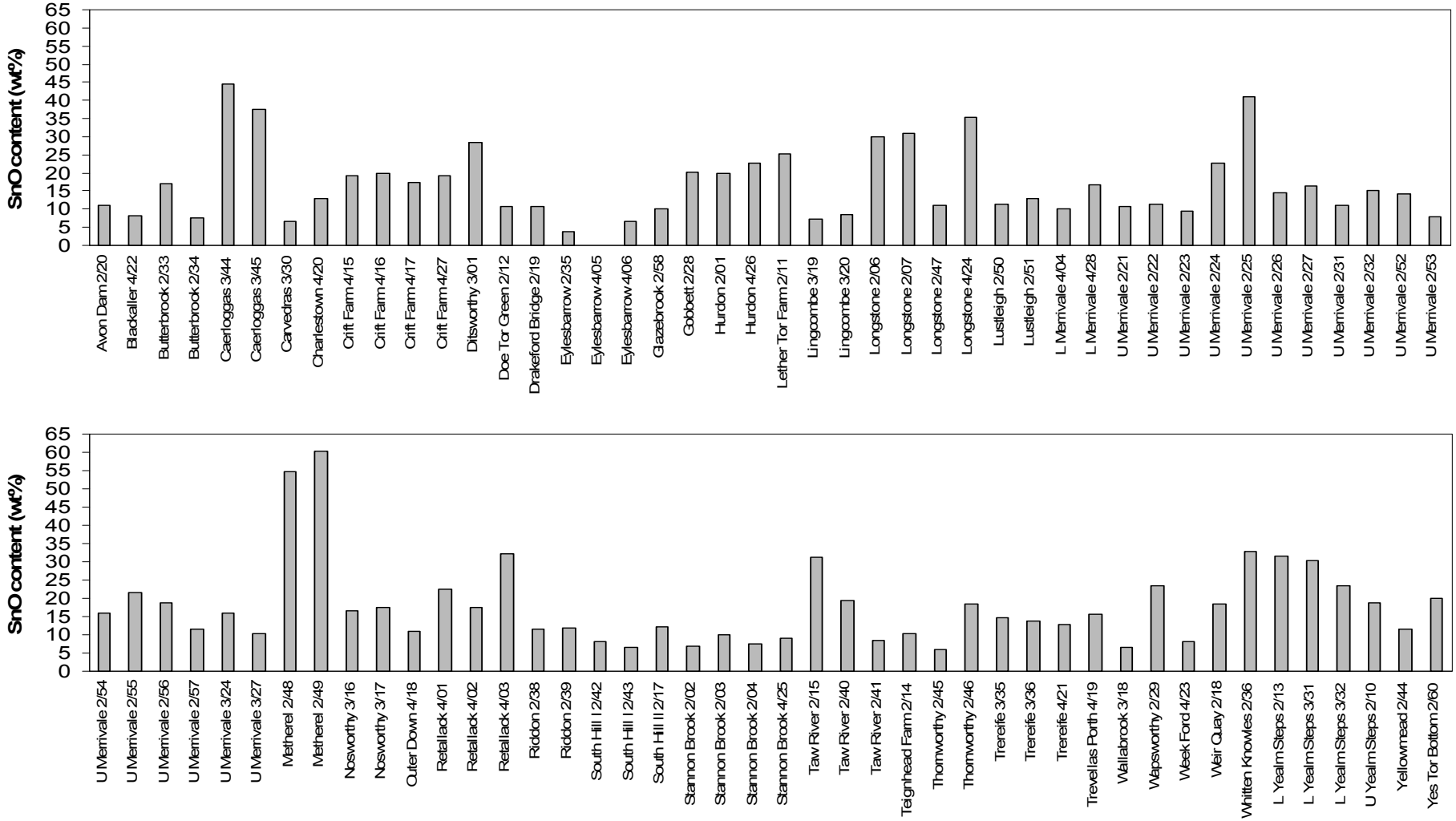


Figure 3.28: Sb_2O_3 content of Archaeological Tin Slags (wt%)

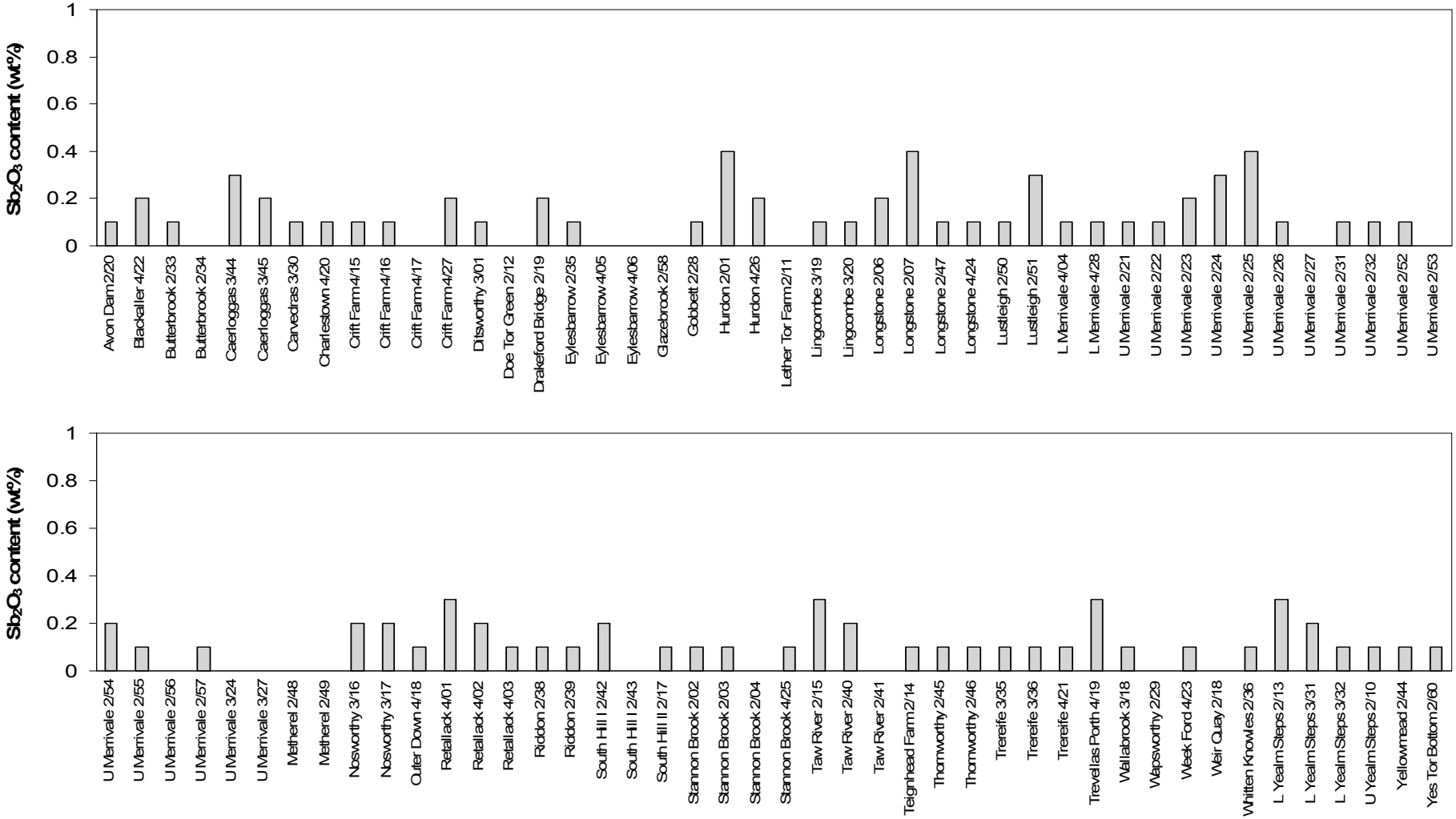


Figure 3.29: WO_3 content of Archaeological Tin Slags (wt%)

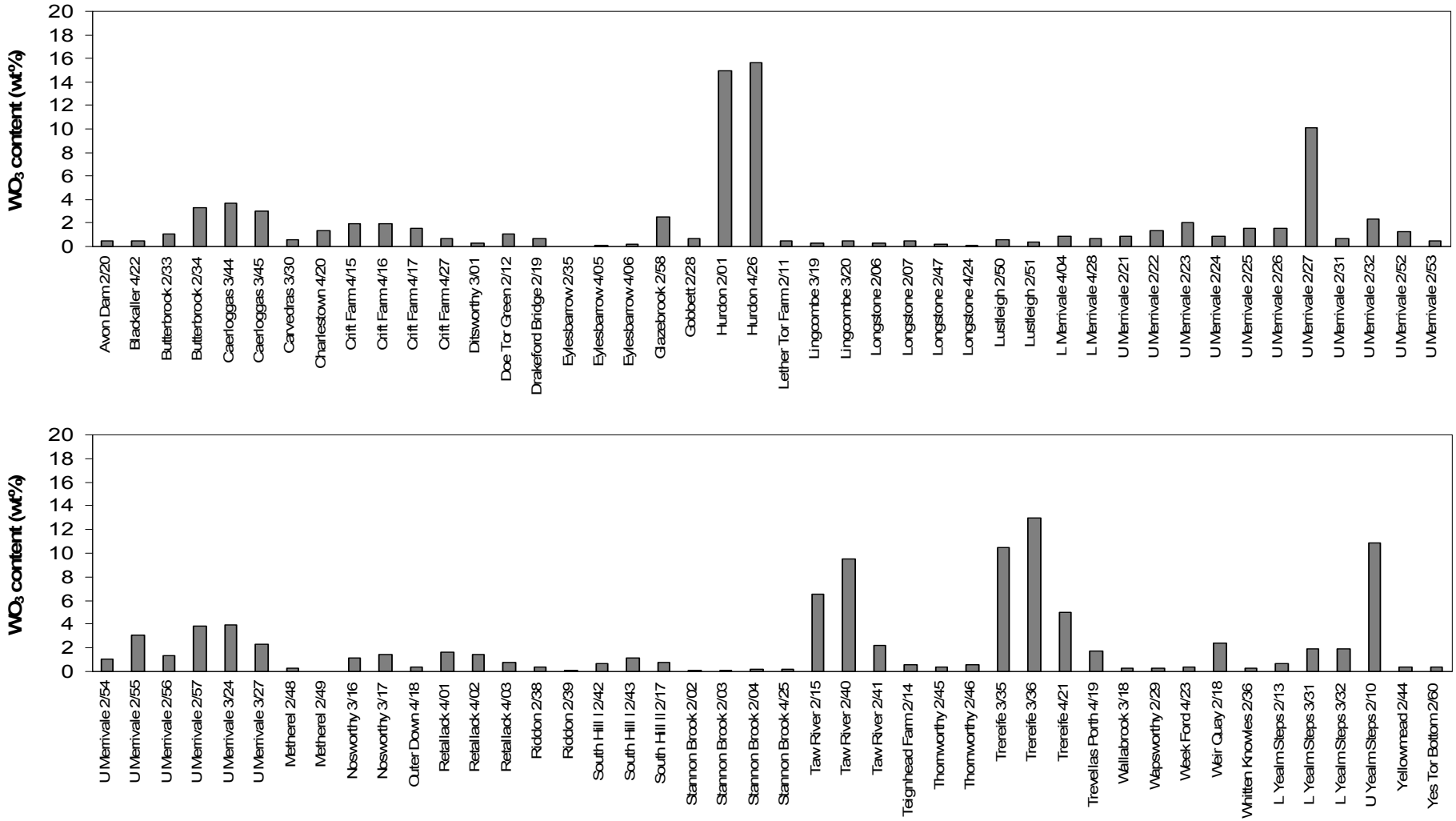


Table 3.3: Ranges of SnO Content in Slags from Different Periods

Slag Type	Early	Blowing House	Reverberatory
Max SnO content (wt%)	44.5	35.3	18.4
Min SnO content (wt%)	17.4	5.8	3.9

sites that have percentages of SnO in the same range as – or indeed exceeding – those of the early slags, but equally there are blowing houses that have very low percentages of SnO, as illustrated in Table 3.3.

Notably, some of the slag from Longstone, thought to be a late blowing mill, has 30-35% SnO compared to the Bronze Age slag from Caerloggas with 37-44%, and the Early Mediaeval Crift Farm slag with 17-20%; by contrast, Stannon Brook, thought to be an early blowing mill, has 7-10%, almost as low as the 19th Century reverberatory slag from Carvedras which has c.7%, and both have considerably less SnO than the Charlestown reverberatory slag at 13%. The amount of variation in SnO content seen within the slag from Upper Merrivale is interestingly broad, even taking into account the evidence that this site operated for an extended period. A discussion of factors that influence residual tin content within slags is to be found in Section 4.1.2.

The absence of any tin in sample 4/05 from Eylesbarrow seems to indicate that it is composed of elements deriving only from the furnace lining; however there are problems with this interpretation if the sample is considered in relation to sample 4/06, which was taken from a different part of the same original block. Sample 4/06 does contain tin, and has a composition not dissimilar to other slags, so taken in isolation might simply be interpreted as slag that has adhered to the furnace wall. However, to judge from the number of mineral inclusions in sample 4/06 (where they are absent in sample 4/05) and the fact that this part of the block exhibited signs of breakage (where the portion that became sample 4/05 was weathered smooth), it is sample 4/06 that

contains material from the furnace wall, and sample 4/05 was external to that. If the sample originated from the base of the furnace, it is possible that there was some separation of the components of the slag under the influence of gravity, which caused the smooth alumino-silicate layer to form over the denser tin-rich portion of the slag.

The percentage of iron oxide present in blowing house and later slags is also highly variable (c.5–37%). In general it appears that early slags have relatively low percentages (<10%); this may to some extent reflect the use in early smelting of alluvial cassiterite, which is likely to have a reduced component of iron minerals.

Smelting temperature is likely to have influenced iron content in the later slags. Low metallic oxide contents are probably a result of strong reducing conditions, which cause both tin and iron to be converted to metal so that they are lost from the slag. For further discussion of iron oxide content in slags, see Section 4.1.2.2.

Small amounts of tungsten are present in almost all the samples, but the samples from a few sites, which include both blowing houses and reverberatory smelters, have in the region of 10-15% tungsten oxide, a level of this element which could have proven problematical to the smelters. The issues associated with tungsten will be discussed further in Section 4.1.2.3.

Titania is present in all the samples. The levels in Cornish slags of all periods are relatively low (0.5- 4.8%), implying a low abundance of titania in the ore bodies of Cornwall, but as Salter (1997) points out, so few analyses of Cornish slags have been carried out it is not currently clear whether low titanium concentrations apply to ores from all the granite masses in Cornwall. Dartmoor slags are much more variable (0.7 – 14.8%). The observation that Devon slags contain more of this element than Cornish slags (Tylecote et al 1989) is thus shown to be over-simplistic. It appears that, with only

a few exceptions, slags from the north and easterly parts of Dartmoor contain higher levels of titania than slags from the southwestern part of Dartmoor. This trend is illustrated in Figure 3.11. A change in the underlying geology of Dartmoor may therefore be proposed as a factor influencing titania content in these slags.

It has also been suggested (Greeves 1981a p259) that elevated levels of titania may be indicative of the use of vein ore, as opposed to alluvial material, however it is debatable whether the analytical data presented here support this argument. Certainly the slags from Whitten Knowles, Metherel, Yes Tor Bottom and Lether Tor Farm - all postulated to be of relatively early date and therefore more likely to have derived from alluvial cassiterite - have relatively low TiO_2 contents, but regrettably the lack of firm dating evidence for these sites means that the relationship cannot be confirmed. Where titania contents are found to cover a range of values from low to high, this could be explained by suggesting that both alluvial and vein ores were utilized at the same site. In contradiction of the argument is the above observation that later sites situated in northeastern Dartmoor tend to have slags with higher TiO_2 levels, as it is in southwestern Dartmoor that the majority of openworks for the extraction of vein ore were located (Gerrard 1997 p78). Reverberatory slags, which almost exclusively derive from vein ores, do not have high abundances of titania; the few reverberatory slag samples examined to date come from sites located in Cornwall or southwest Devon where the local geology confers a low titania content.

Modern tin smelting makes use of lime (CaO) as a flux, but the amount of CaO found in archaeological slags of all ages is actually rather low (<5%, more usually 1-2%). It has been remarked elsewhere (e.g. Tylecote 1989), but it is worth reinforcing the point,

that the deliberate addition of lime flux to the charges of blowing house furnaces and to most reverberatory furnaces did not occur. For further discussion see Section 4.1.2.3.

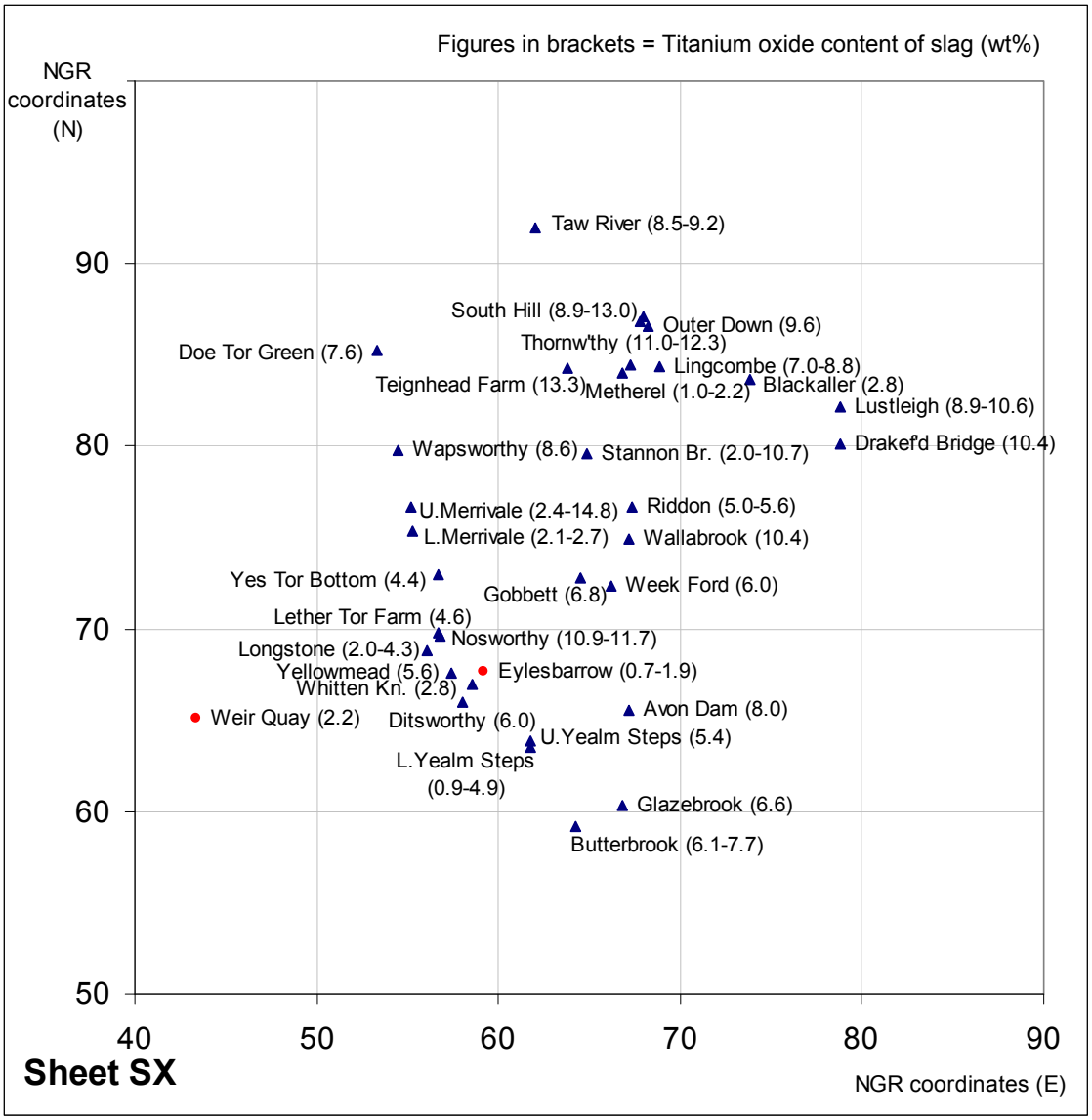


Figure 3.30: Map of Dartmoor Tin Smelting Sites showing changes in TiO_2 content with geographical location (reverberatory smelters are shown in red)

For many of the sites under consideration there is only a single sample, thus it is not possible to determine the extent of variation in composition for slag from that site. Where multiple slag samples from a particular site were analysed, however, it is possible to see that while there is a degree of heterogeneity at all sites, the level of

disparity varies widely. A comparison of the variations of the major chemical species in multiple samples from two sites, Crift Farm (4 samples) and Upper Merrivale (17 samples), is made in Table 3.4. It is clear from the differences in the ranges of the oxide contents (calculated from mean oxide compositions presented in Table 3.2) that the Crift Farm slags are considerably more uniform in composition that the Upper Merrivale slags (see Figure 3.31).

Table 3.4: A Comparison of the Ranges of Oxide Contents in Slags from Crift Farm and Upper Merrivale

Oxide	Range of Oxide Content (wt%): Crift Farm	Range of Oxide Content (wt%): Upper Merrivale
Al_2O_3	5.8	12.8
SiO_2	1.9	25.5
TiO_2	0.6	13.2
FeO	2.7	27.6
SnO	2.4	33.2
WO_3	1.2	9.6

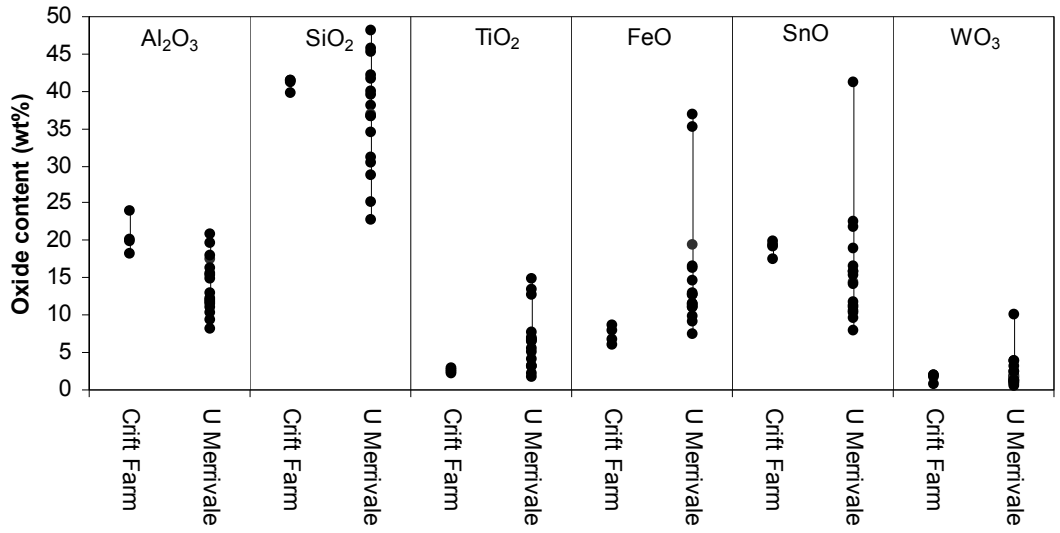


Figure 3.31: A Comparison of the Ranges of Oxide Contents in Slags from Crift Farm and Upper Merrivale

This high level of heterogeneity in the sample set from Upper Merrivale must ultimately result from the use of ores of an inconsistent nature. (Changes in smelting conditions within the furnace could potentially lead to compositional differences in slags, but such changes as occurred would to a large extent be directly related to the original ore composition.) Thus either local ore deposits were of variable quality, or the ore derived from diverse sources encompassing a wider geographical area. By contrast, the similarity between the Crift Farm samples would imply a relatively consistent, and thus local, ore source.

The apparent randomness of the quantities of particular elements in the different types of slags means that it is not always particularly useful to consider any one element in isolation. Patterns may, however, be discerned when the bulk slag composition is considered. The following figures (Figures 3.32 to 3.38) show the relative proportions of the main components of slags deriving from furnaces of various types and from blowing houses in different geographical areas. (Minor chemical components have been disregarded and the data normalized.) Relative uniformity is indicated on the plots by clustering of the data points (e.g. Crift Farm on Figure 3.32 and Lustleigh on Figure 3.36), while widely scattered points indicate a site having samples with a more heterogeneous composition (e.g. Upper Merrivale on Figure 3.34 and Lower Yealm Steps on Figure 3.35).

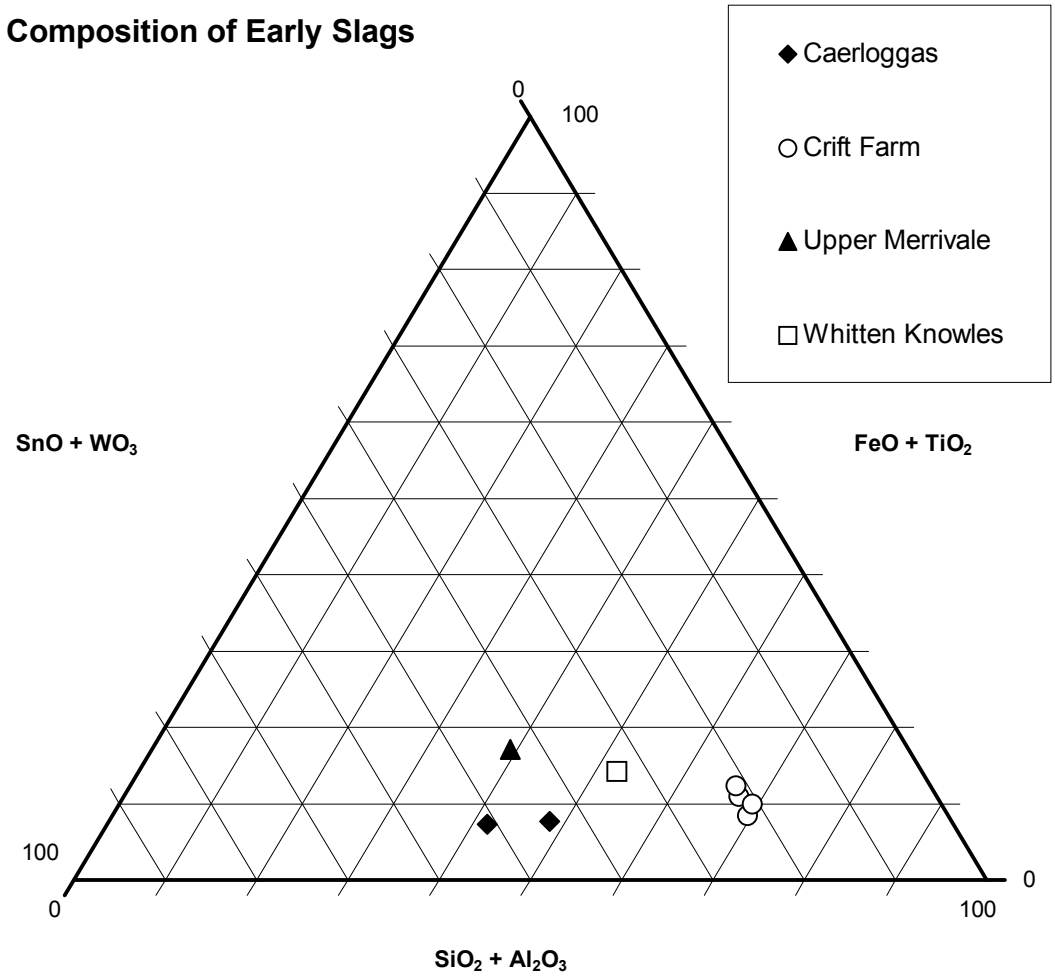


Figure 3.32: Ternary Plot of Main Components of Early Slags

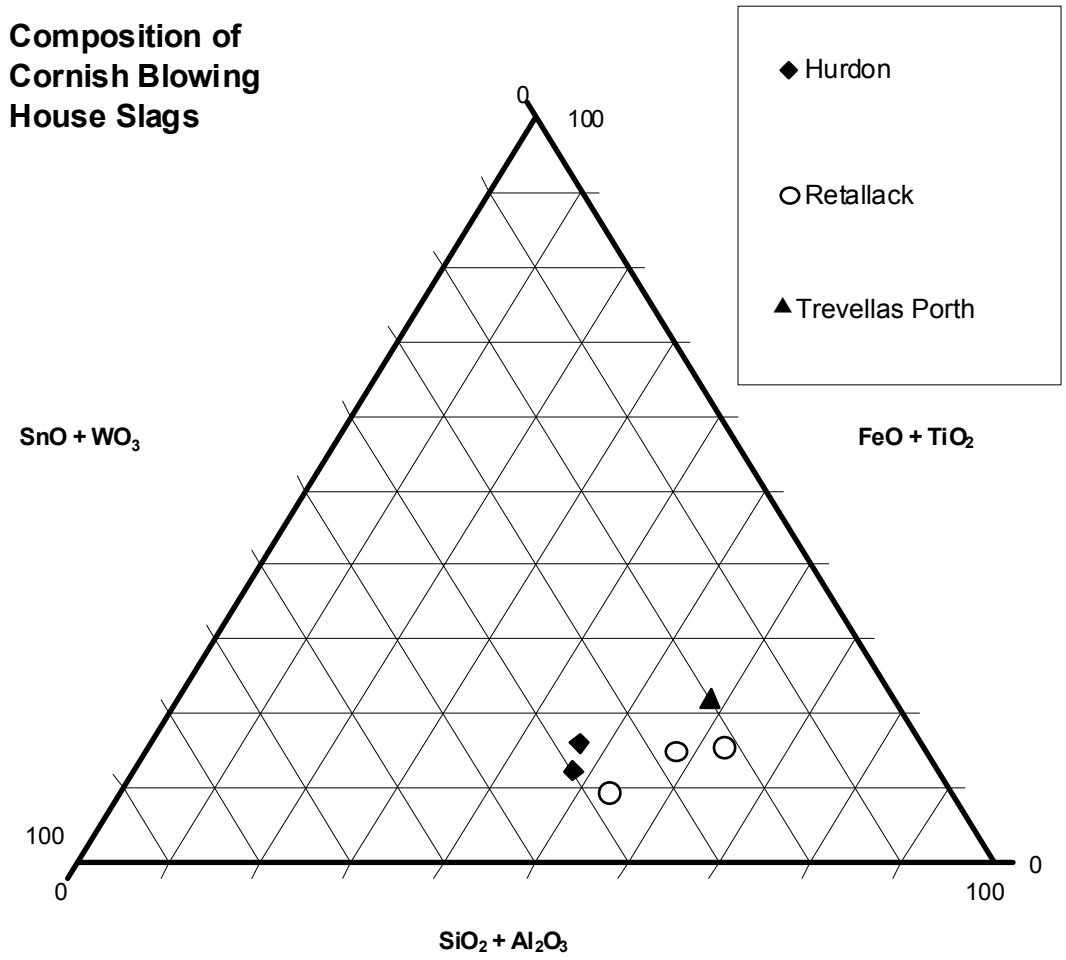


Figure 3.33: Ternary Plot of Main Components of Cornish Blowing House Slags

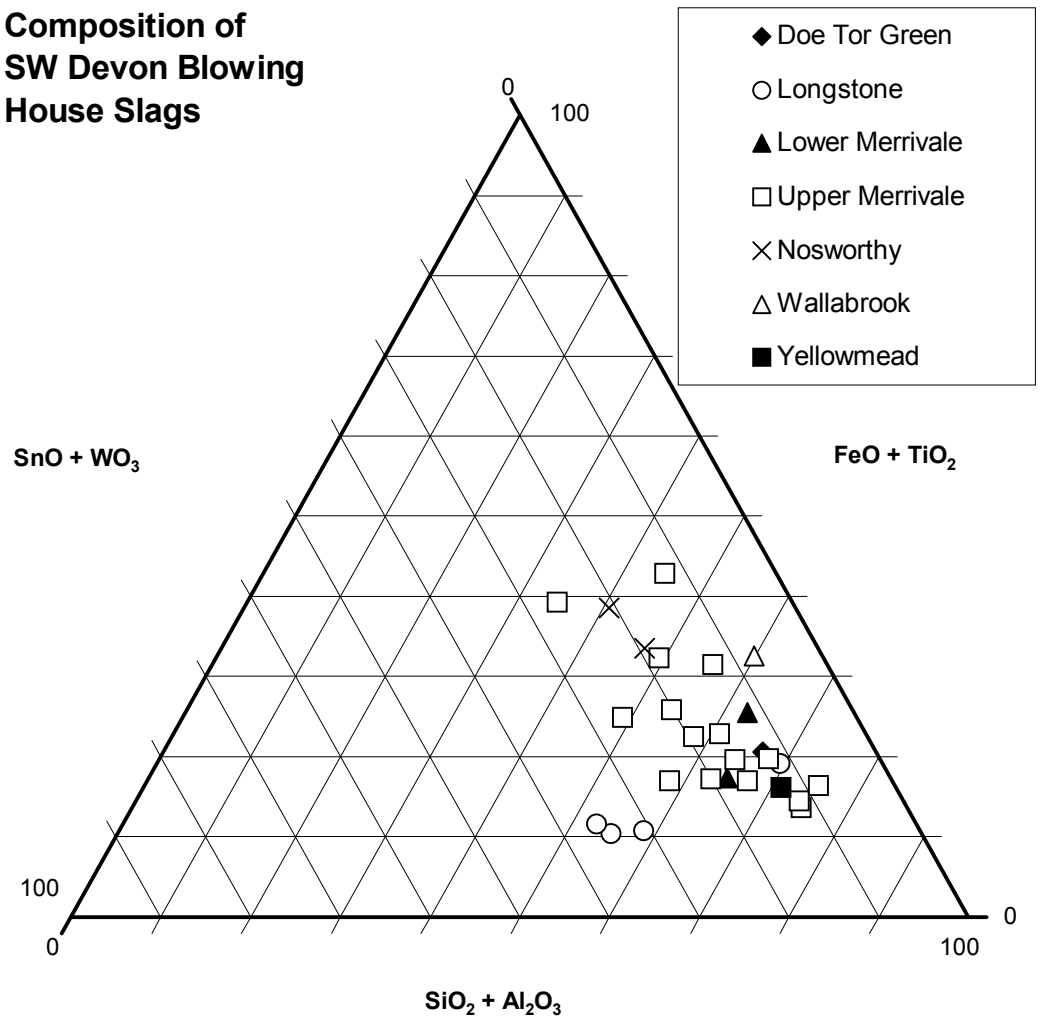


Figure 3.34: Ternary Plot of Main Components of Southwest Dartmoor Blowing House Slags

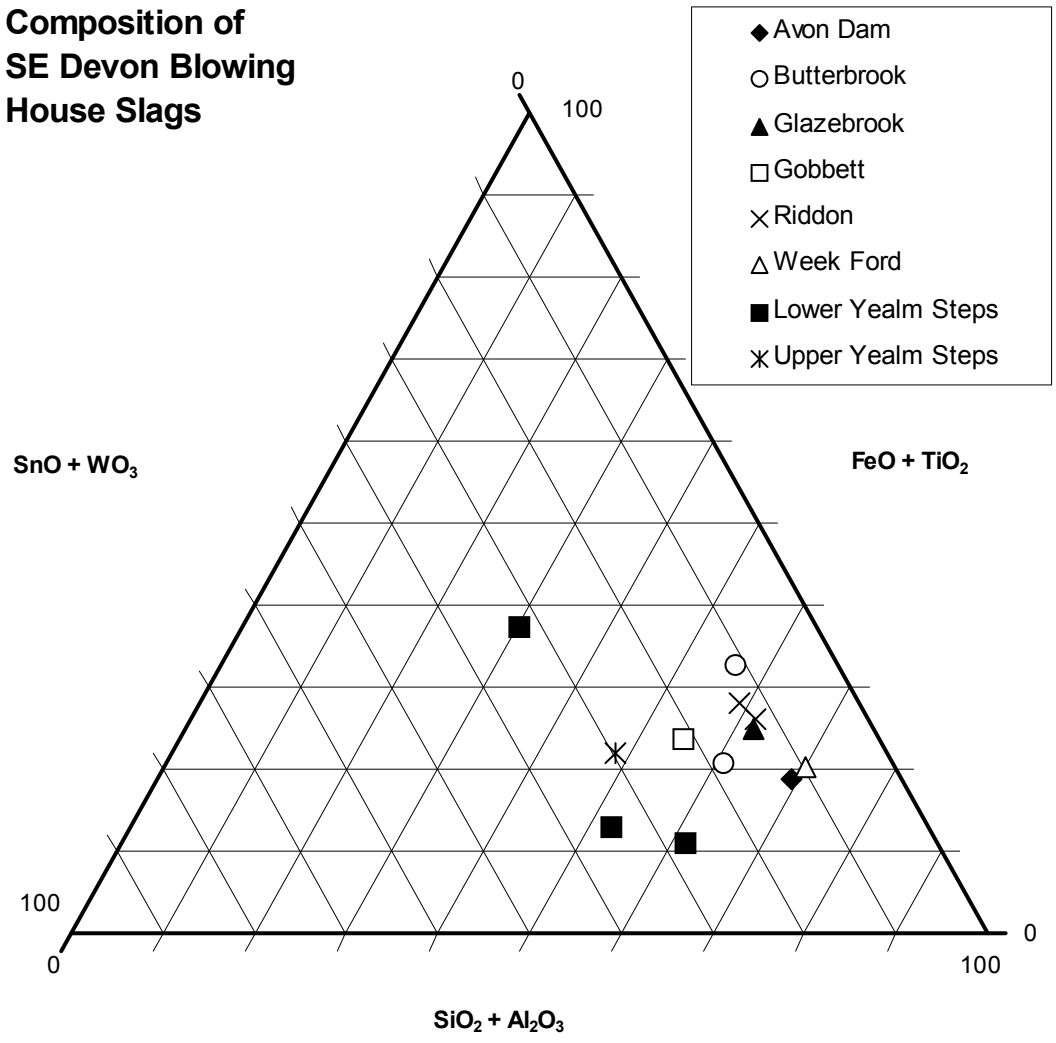


Figure 3.35: Ternary Plot of Main Components of Southeast Dartmoor Blowing House Slags

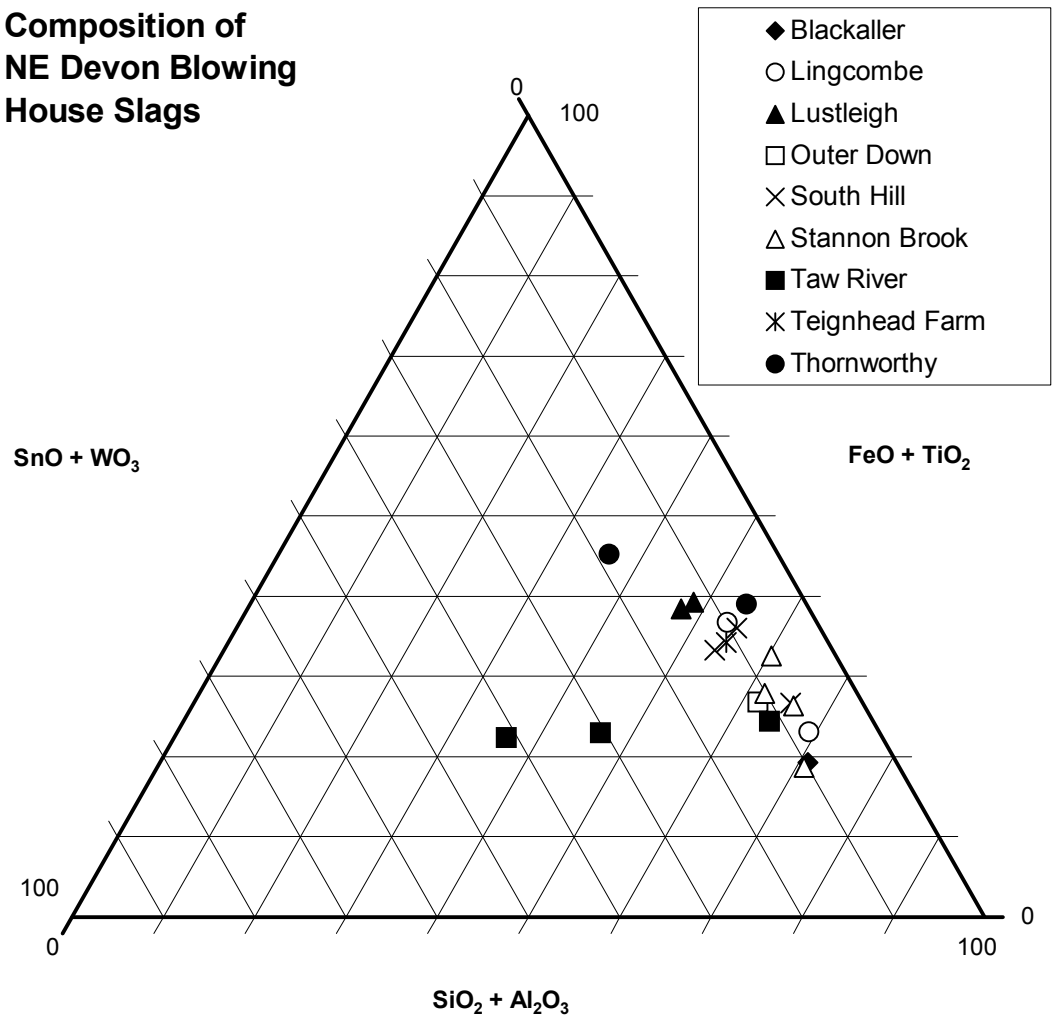


Figure 3.36: Ternary Plot of Main Components of Northeast Dartmoor Blowing House Slags

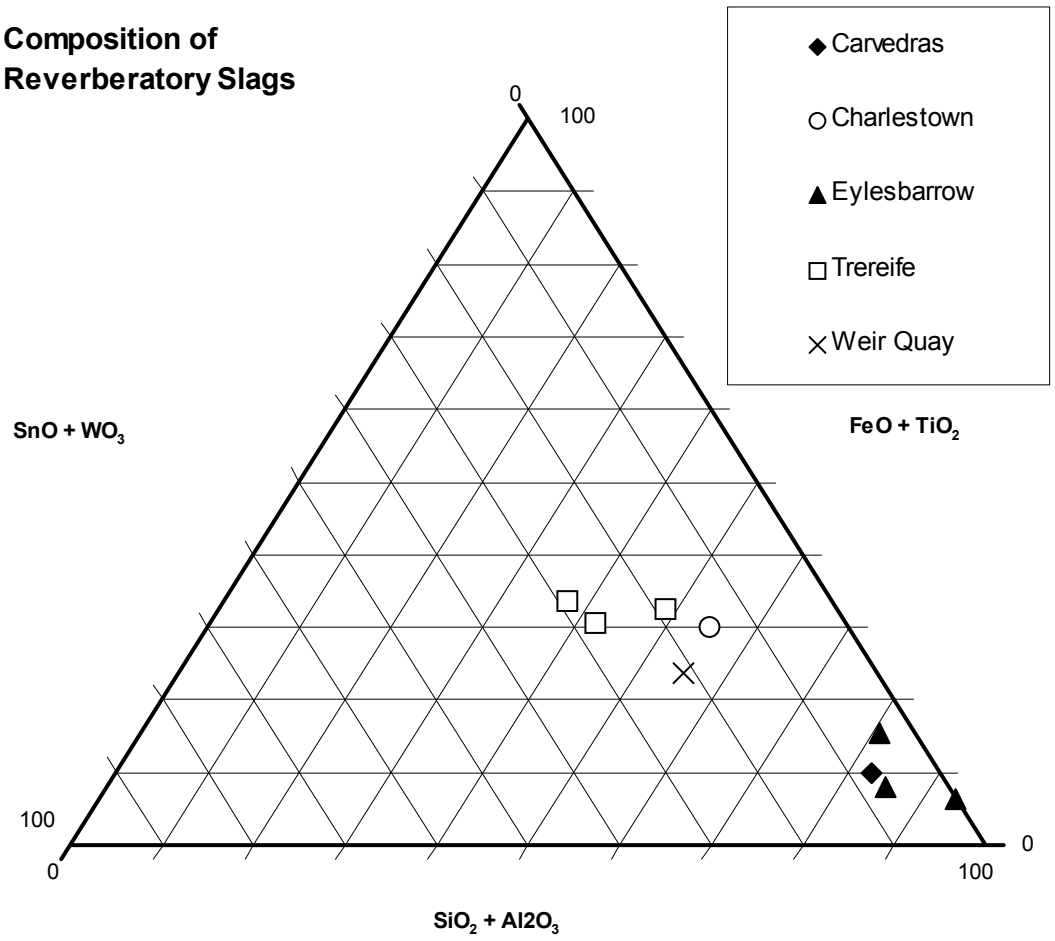


Figure 3.37: Ternary Plot of Main Components of Reverberatory Slags

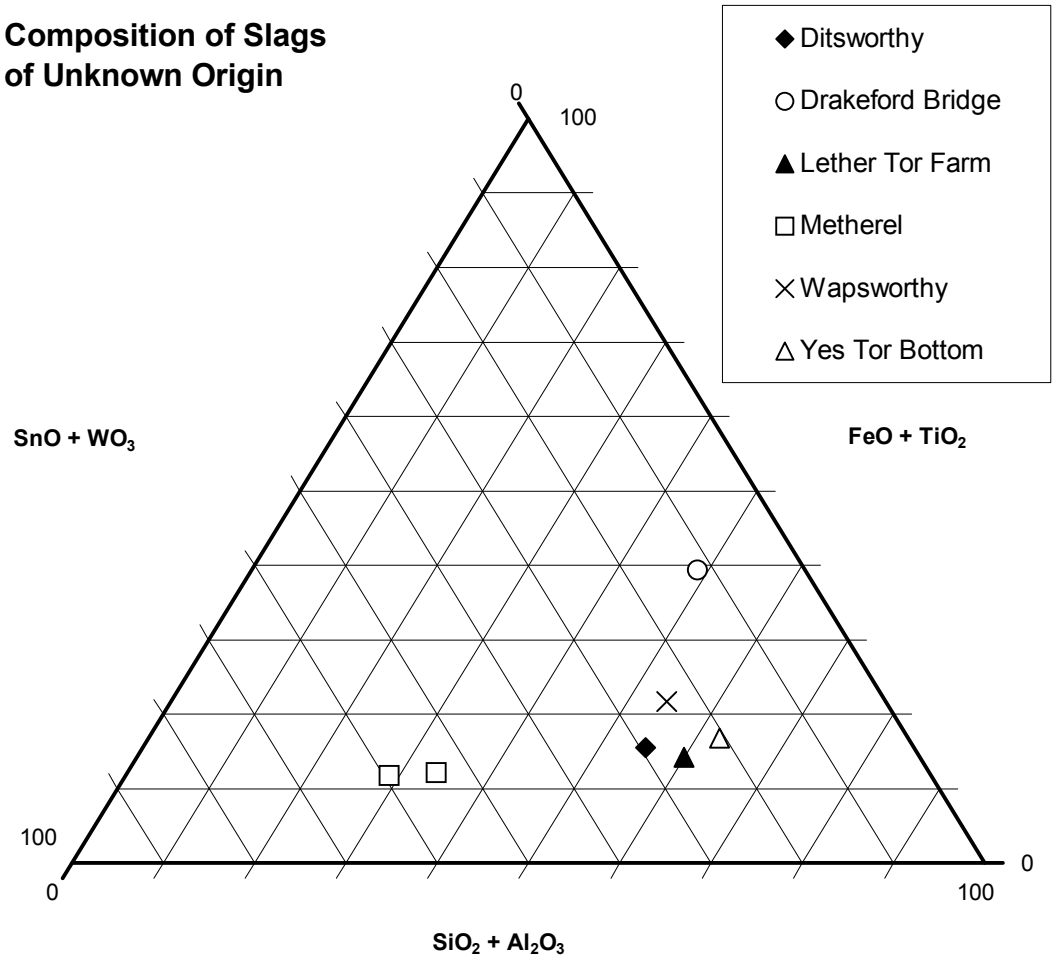


Figure 3.38: Ternary Plot of Main Components of Slags of Unknown Origin

The early slags and Cornish blowing house slags are similar in that they both group along the bottom axis of the ternary diagram. The Dartmoor slags are limited to the right hand side of the bottom half of the plot, but are mainly further from the bottom axis than the early and Cornish slags. The reverberatory slags fall within a similar area, except for Eylesbarrow, which plots in the extreme bottom right of the diagram. If these distributions are applied to the sites where the slag was produced by an unknown technology, it would imply that Metherel was an early smelting site, the Drakeford Bridge slag derived from a blowing house or reverberatory smelter, and that the Ditsworthy, Lether Tor Farm, Wapsworthy and Yes Tor Bottom could either be early or derive from blowing houses. For further discussion of this point, see Section 4.1.4.

Another pattern becomes apparent when the relationship between slag composition and slag microstructure is considered. Although this relationship is complex, and there are also some deviations from the general trend that may result from differences in cooling rate, it can be seen that high iron content and/or high titanium content in a slag tends to promote the formation of slags with a crystalline character. By contrast, slags with higher proportions of tin in comparison to their iron/titanium content tend to be glassy, or have only very isolated patches of a different phase.

These trends are illustrated in Figures 3.39 and 3.40, which show plots of SnO content against FeO and SnO against combined FeO and TiO_2 content respectively for slag samples that, when examined under the optical microscope, appeared to be a) wholly glassy, b) glassy with isolated patches of a different phase contained within the glassy matrix or c) entirely covered with crystalline phases (i.e. feathery phases, dendrites or crystal laths). Clearly, there is a large amount of overlap between the three data series, but this is to be expected given that other factors also influence microstructure, and that not all of the chemical species present in the slag have been considered.

It appears from these plots that there is a minimum FeO to SnO ratio of 0.4 below which crystalline phases will not manifest, and only a single crystalline sample (Taw River 2/15) has a ratio so low; the remainder have ratios of 0.6 and higher. Approximately half of the glassy slags have FeO/SnO ratios of 0.6 and below.

The minimum FeO + TiO_2/SnO ratio for crystal formation appears to be 0.7, again this low value is for sample 2/15; all other crystalline samples have ratios exceeding 1.1. Two thirds of the glassy samples have ratios of 1.1 and below.

Figure 3.39: Graph of FeO content against SnO content of Slag Samples with Different Microstructures

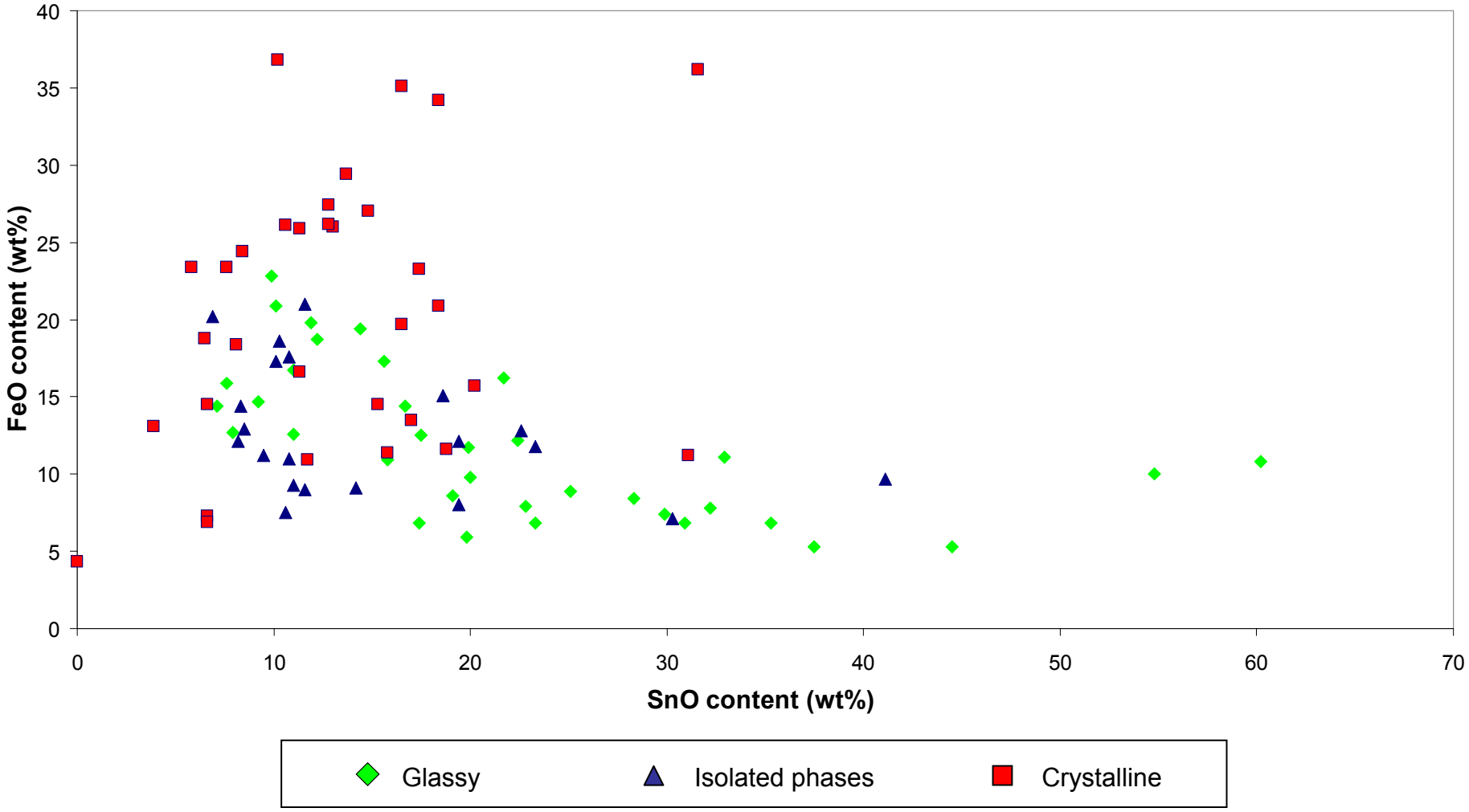
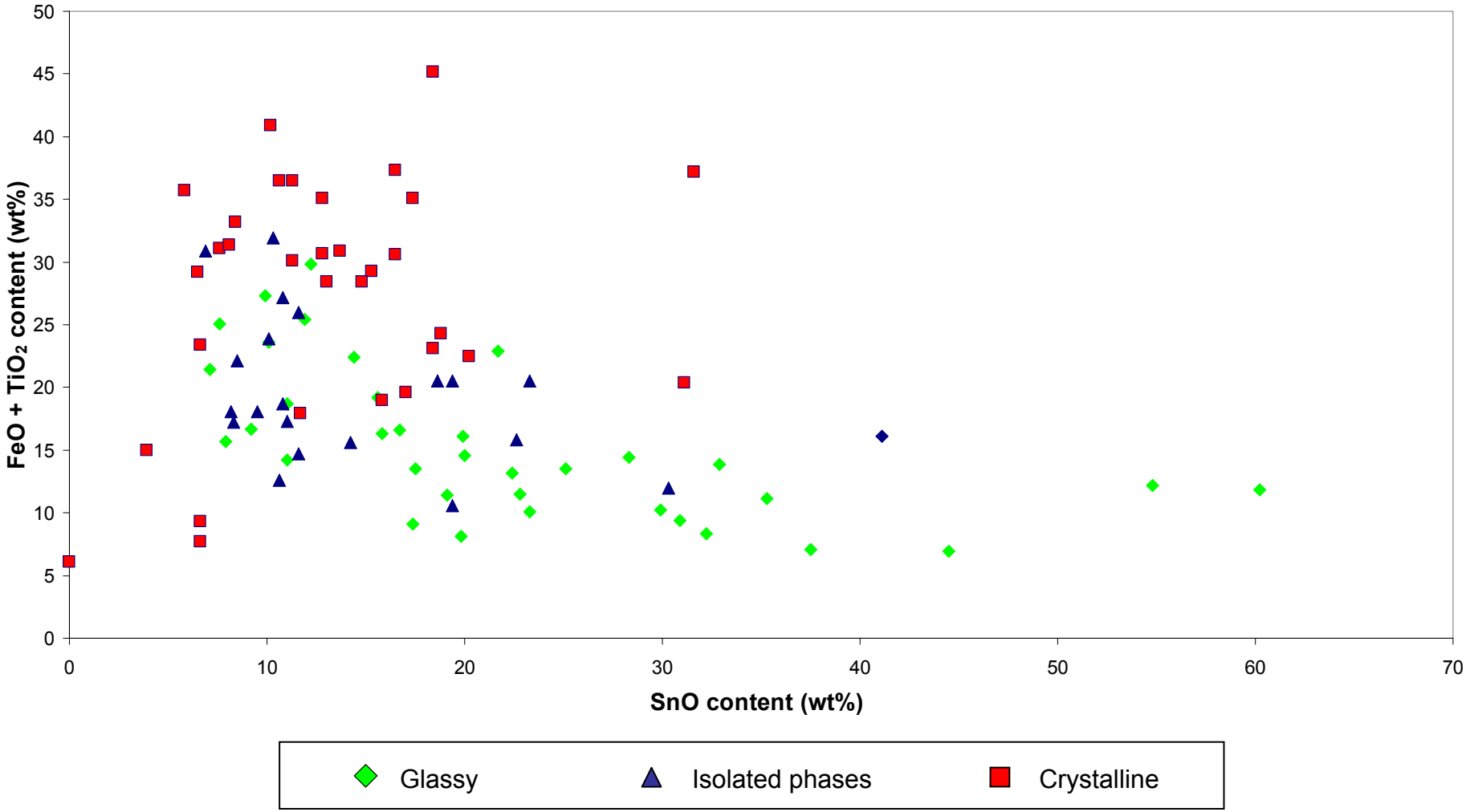


Figure 3.40: Graph of FeO + TiO_2 content against SnO content of Slag Samples with Different Microstructures



Another very general trend can be observed when the blowing house slags of Dartmoor are considered as a group: the relationship between the FeO and SnO content of slags and geographical location. Plots of FeO content against SnO content (Figure 3.41) show that there is a loose clustering of the slags from more northerly and easterly sites, which tend to have lower tin and higher iron compared to the majority of samples from blowing houses situated in more southerly and westerly parts of Dartmoor. There is, however, some overlap between the two groups, and some samples do not fall within the clusters.

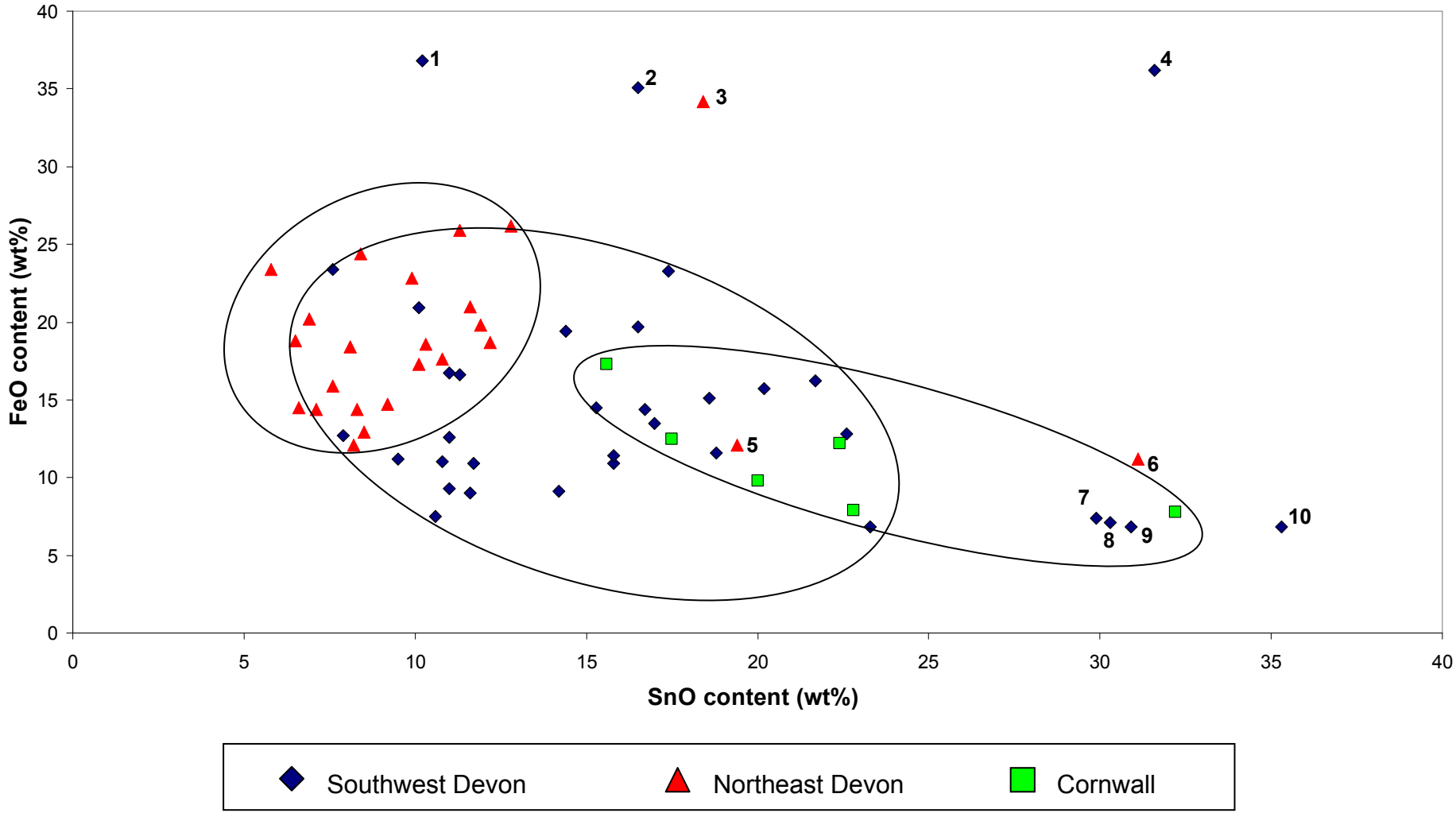
In Figure 3.41 the outliers numbered 1 and 2 are both samples from Upper Merrivale; number 3 is a sample from Thornworthy; 4 and 8 are samples from Lower Yealm Steps; 5 and 6 are two of the three Taw River samples; numbers 7, 9 and 10, clustered at the bottom right of the plot, are three of the four samples from Longstone.

Samples that have levels of iron or tin dissimilar from other slags in the same geographical area may occur because the ore from which the slag derived contained particularly high levels of the element in question compared to the bulk of ores from that location. Alternatively, as the slag composition is determined by area analysis, the presence of unusually high numbers of very small tin prills would affect the results.

It is not possible to see similar relationships in the data for the Cornish and reverberatory slags, if any such exist, owing to the very small number of samples available. The few samples from Cornwall that have been examined form a loose cluster, although there is much overlap with the south-western Dartmoor cluster.

A discussion of how differences in FeO/SnO ratios arise, and how these ratios relate to geographical location is presented in Section 4.1.2.2.

Figure 3.41: Graph of FeO content against SnO content of Slag Samples from Blowing Houses in Different Geographical Locations



3.1.4.2: Analysis of Slag Phases

As noted in Sections 3.1.2 and 3.1.3, tin smelting slags are not all uniform in appearance: striations (flow bands) and crystals occur in many samples. Each of these types of phase will be discussed in turn.

Flow Bands

Results of the analysis of different phases in those slag samples that contain flow bands are presented in Appendix 5. The elements that are enhanced in the light flow bands (as viewed using backscattered electron imaging) are highlighted in yellow, and elements enhanced in the dark bands are highlighted in pink. A darker shade of either colour indicates an increase of 1% or more in the concentration of that element compared to the adjacent band. The data were collected to determine the extent of variation within a pair of bands and to discover whether there were any associations between different elements.

The data indicate that partitioning of elements between light and dark bands is only partial. For a discussion of this point see p294. The maximum differences in concentration between pairs of flow bands have been calculated for the major chemical species and are presented in Table 3.5. Differences in the concentrations of the major chemical species in pairs of flow bands in individual slag samples are shown in Figures A5.1 to A5.6 in Appendix 5.

Given the extent of variation in composition within a flow banded slag, it is likely that attempts to detect potential increases in tin concentration around the edges of slag samples, where the slag may have been in contact with pooled molten tin, would be unsuccessful, the variation in flow bands producing a masking effect.

Backscattered SEM imaging shows contrasts between high and low atomic mass elements. In practice, in the majority of the data sets given in Appendix 5, silica and alumina, both of which are light elements present at relatively high concentrations, tend to dominate in the dark flow bands. As tin is usually the most abundant high atomic mass element in the slags, the light bands are those that are enhanced in tin by >1%. Exceptions to this are seen in the bands of Upper Merrivale sample 2/53, where tin is very slightly (0.1-0.2%) enhanced in the dark band. Problems with electrical charging were experienced with this sample and it is possible the analyser beam drifted so that the two bands are not well resolved.

Table 3.5: Difference in Concentrations between Light and Dark Flow Bands

Element	**Maximum difference between light and dark flow band (%)**
Aluminium	3.7
Silicon	8.7
Titanium	3.9
Iron	3.1
Tin	16.7
Tungsten	3.7

Note: Difference calculated as the highest percentage concentration of a chemical species minus the lowest percentage concentration of that species in a pair of adjacent flow bands.

Lower Yealm Steps sample 3/31 offers another exception: here the differences between the second pair of bands are slight (<0.5%), so possibly the enhancement of 0.4% tungsten caused the light band to appear bright despite it having 0.2% less tin.

In Crift Farm sample 4/15 the appearance of the second light band is possibly more to do with the presence of enhanced tungsten than of tin.

There is no correlation, either positive or negative, between enhanced levels of tin and concentrations of tungsten in flow bands. The same is true for iron.

In cases where flow bands are visible with the naked eye, it is probable that the light and dark bands are not the same as those apparent using backscattered scanning electron microscopy. Visually observable dark colours in slags may be caused by enhanced levels of mafic minerals (i.e. iron and magnesium); silicate or alumino-silicate rich slag would appear pale.

Feathery/Needle-like Phases

In those slags where the phases are more distinct, i.e. where feathery/needle-type, dendritic or crystalline phases are present, partitioning of elements occurs to a greater extent. Analysis of these phases has shown how different chemical species are distributed within the slag. Results of analysis of feathery/needle-type phases and the surrounding matrix are presented in Appendix 6; results for dendrites are presented in Appendix 7 and crystalline laths in Appendix 8.

Despite containing a lower proportion of high atomic number elements, the feathery phases appear lighter than the surrounding matrix, with one exception (Taw River 2/15), which is possibly because tin and tungsten are very much more concentrated in the matrix of this sample compared to the matrices of other samples.

All feathery phases contain enhanced in TiO_2, which is almost always accompanied by V_2O_5. The surrounding matrix is enhanced in Al_2O_3, SiO_2, and in the majority of samples, a much higher proportion of SnO. K_2O and CaO are also, with rare exceptions, enhanced in the matrix.

Iron and tungsten may be higher in either phase; magnesium and manganese commonly partition with iron.

Again, it is observed that partitioning of elements is not complete; however, as shown in Table 3.6, it is more marked than occurs in the flow bands. Figures A6.1 to A6.6 in Appendix 6 illustrate the range of variation in concentrations of the major chemical species between feathery/needle-like phases and the surrounding slag matrix in individual slag samples.

Table 3.6: Difference in Concentrations between Light Feathery Phase and Dark Matrix

Element	Maximum difference between light and dark phase (%)
Aluminium	13.5
Silicon	41.6
Titanium	33.1
Iron	27.8
Tin	30.1
Tungsten	8.8

Dendrites

The dendrites, which, like the feathery phases, appear pale against a dark matrix, are all enhanced in FeO, and, with one exception TiO_2: Eylesbarrow sample 2/35, which has an unusual composition for a tin slag; the majority of its constituent elements possibly derived from the furnace lining rather than the charge. Higher concentrations of FeO and TiO_2 are almost always accompanied by higher levels of V_2O_5 and MnO.

The surrounding matrix contains greatly enhanced SiO_2. In the majority of samples matrix Al_2O_3 is enhanced, usually by more than 10%. Again Eylesbarrow 2/35 is an exception. Another is Upper Merrivale 3/27, which is unlike the other dendritic slags in

that some portions of the slag appear to contain both a dendritic phase and a crystalline phase (see p291). Na_2O, K_2O, P_2O_5, CaO, SnO and WO_3 are also, with rare exceptions, enhanced in the matrix**.**

There is a similar level of element partitioning to the feathery phases as shown below in Table 3.7. Figures A7.1 to A7.6 in Appendix 7 illustrate the range of variation in concentrations of the major chemical species between dendritic phases and the surrounding slag matrix in individual slag samples.

Table 3.7: Difference in Concentrations between Light and Dark Phases in Dendritic Slags

Element	Maximum difference between light and dark phase (%)
Aluminium	11.3
Silicon	43.6
Titanium	38.5
Iron	51.5
Tin	24.2
Tungsten	6.7

Note: The results do not include Eylesbarrow sample 2/35 owing to its dubious status as a tin slag.

Partitioning of the elements in the 3-phase portion of the Upper Merrivale sample is as follows. The dendrites have higher Al_2O_3, TiO_2, V_2O_5 and FeO; thus the difference between this and other dendritic slags is an increased proportion of Al_2O_3 in the dendrites. The dark matrix has enhanced SiO_2, K_2O, CaO and SnO, while the mid coloured matrix is enhanced in MgO, SiO_2, MnO and FeO, i.e. there is further partitioning of many of the elements that normally compose the single phase. It is interesting also that even in the portion of this slag that looks similar to other 2 phase dendritic slags the partitioning of the elements is rather different: K_2O, CaO, SnO and WO_3 are enhanced in the dendrites rather than the matrix**.**

Crystalline Phases

In the fully crystalline slags, partitioning of elements is often extremely marked, as shown in Table 3.8. For compositions of phases in crystalline slags, see Appendix 8. Plots illustrating the variation in concentrations of the major chemical species between distinct crystalline phases in individual slag samples are presented in Appendix 8 (Figures A8.1 to A8.6).

Table 3.8: Difference in Concentrations between Phases in Crystalline Slags

Element	Maximum difference between two phases (%)
Aluminium	57.1
Silicon	37.5
Titanium	14.2
Iron	60.5
Tin	60.4
Tungsten	63.9

Note: The results do not include Eylesbarrow samples 2/35 and 4/05 owing to their dubious status as tin slags.

Two blowing house slag samples were found to have a fully crystalline microstructure: Upper Merrivale sample 2/27 and Lower Yealm Steps sample 2/13. There are some striking similarities in the compositions of the phases present, but also some differences. Both contain dark grey laths, mainly FeO and SiO_2, accompanied by the bulk of the small quantity of MgO and MnO present in the sample. Both also have a mid-grey phase, mainly SnO and SiO_2, with some FeO and Al_2O_3, and minor amounts of Na_2O, K_2O and WO_3. The lightest phases in the Upper Merrivale sample contains very high WO_3, most of the MoO_3 and ZrO_2 (all three of which are much higher overall than in sample 2/13), with some SiO_2 and FeO. The Lower Yealm Steps sample appears under optical and normal beam scanning electron microscopes to contain a third phase, but backscattered electron imaging shows only two phases: the pale sub-

rectangular crystals visible in the optical image could not be distinguished from the mid-grey phase. Owing to the very small size of the crystals making up this lightest phase, no separate determination of composition was obtained. Based upon the shape of the crystals, and the lack of contrast between them and a high tin content phase when using backscattered electron imaging, they are possibly tin oxide.

The other crystalline samples are all reverberatory slags. Their crystalline structures are quite complex, with marked differences from the blowing house slags and also from each other, although there are still some similarities in that certain phases are common to most samples.

The Eylesbarrow samples, as mentioned previously (p268), are probably slag that has adhered to furnace lining materials. They each contain two phases, but their quite different bulk compositions have influenced the composition of their respective crystal phases. The bulk composition of sample 2/35 is dominated by iron, silicon and aluminium. The optically light phase consists of very high FeO with the greater portion of the Al_2O_3 and MgO; the dark phase contains the majority of the SiO_2, which is accompanied by some Al_2O_3. The tin-free sample 4/05 is almost wholly composed of SiO_2 and Al_2O_3 with <5% FeO. In the light phase SiO_2 is greatly enhanced; in the dark phase, Al_2O_3; the distribution of FeO being roughly equal. The final sample, 4/06, is very similar to 4/05, save that it also contains some SnO, slightly more of which is found in the light crystals compared to the dark.

The similarity of the phases in terms of the atomic numbers of their component elements results in a lack of contrast between the phases when examining these samples using backscattered electron imaging.

The Carvedras slag has three separate phases visible. The light phase has very high SiO_2 with some Al_2O_3, FeO and SnO, and slightly enhanced Na_2O, MgO, K_2O, CaO and TiO_2. The mid coloured phase contains very high Al_2O_3 with some SiO_2. The two data sets for dark crystals show more variation than for the light and mid phases. The first dark crystal actually appears to have a similar composition to the adjacent light crystal, save that it has enhanced MoO_3. The second dark crystal more closely resembles the adjacent mid coloured crystal. Possibly there are two types of crystal that appear dark, suggesting variation within the slag composition much as is observed in other types of slag, but it must also be considered that there may be some interference from adjacent crystals owing to the very small size of the crystals being analysed; the smaller of the two dark crystals (No 2) measured only c.20 x 20 μm.

Two of the Trereife samples (3/35 and 3/36) appear very similar, which is not entirely unexpected given that they derived from different parts of the same large block, however it does imply a generally uniformity, both in composition and in the physical conditions allowing crystals to form, between the upper and lower parts of the molten slag layer.

Six phases appear to be present. Type 1 are large pale sub-rectangular crystals that contain extremely high WO_3, much of the MoO_3 and ZrO_2, and some SiO_2 and FeO (this is similar to a phase present in Upper Merrivale 2/27). Type 2 consists of small regular crystals, but there appears to be some variation in composition between the three examined. As these crystals were of limited size it is possible that there has been some interference from adjacent phases. All three contain medium amounts of SiO_2, FeO (particularly high in the third crystal), ZrO_2, MoO_3 and SnO (particularly high in the second crystal along with Al_2O_3), while the first crystal has very high WO_3. Type 3

are large dark crystals, similar in composition to the dark crystals in the two blowing house slags. These are very rich in FeO, with some SiO_2, and contain the majority of the MgO and MnO. Type 4 crystals are large mid coloured crystals, high in SnO with enhanced Al_2O_3 and SiO_2, some FeO and WO_3, and the much of the K_2O and CaO. Type 5 crystals appear the lightest and have very similar compositions to the Type 4 crystals: they contain almost as much SnO, have enhanced Al_2O_3 and SiO_2, with some FeO and WO_3, and most have slightly higher MoO_3. (This light phase is actually similar in composition to the dark phase in the Trereife 4/21 and Charlestown 4/20 slags, see below). Only one example of Type 6 crystal was analysed; it appears in sample 3/36 as a dark crystal (indistinguishable by imaging alone from Type 3) and is largely Al_2O_3 with FeO.

The third sample from Trereife, 4/21, is rather different from the other two in that it has two obvious crystal phases, but these are associated with dendritic structures in a matrix. The light crystals consist of very high FeO with enhanced Al_2O_3 and TiO_2, while the dark crystals contain the majority of the SiO_2, SnO and WO_3, with some Al_2O_3 and FeO. In fact, this sample more closely resembles the slag from Charlestown than it does the other piece of slag from Trereife.

Charlestown is also a two-phase slag, the light phase containing high TiO_2 (the only crystalline sample with TiO_2 >10%), high FeO and some Al_2O_3. The dark phase is high in SiO_2 with some Al_2O_3 and FeO, plus high SnO accompanied by the majority of the WO_3. Again, there is a suggestion of dendritic structures associated with the crystals.

It was suggested above (p243) that low viscosity melts might be more uniform than high viscosity melts because any chemical species that were initially present in uneven concentrations would be more mobile within the melt. No real differences could be

discerned from the data gathered using area scans. However, the use of spot analysis to identify individual phases, which focuses upon a much smaller area of the slag sample, does permit a comparison of the levels of heterogeneity in the different types of slag (flow banded, feathery phased, dendritic and crystalline). The results, given in Appendices 5-8, do not support the above assertion.

It is probable that flow bands are an artefact of incomplete mixing of different minerals from the ore in a melt that, based on the observed morphologies of slags containing these features, was highly viscous. These slags certainly exhibit some heterogeneity in their composition. However, this is far exceeded by the levels of variation observed in crystalline slags.

The extent to which elements are partitioned in the different types of slag may be explained in terms of ion mobility in the melt. Crystal formation requires the component chemical species to have a high degree of mobility, and the observed morphologies of the crystalline slags do suggest a comparatively fluid melt, thus a high level of partitioning is theoretically possible. At the opposite end of the spectrum of microstructures, a glassy slag forms as a result of chemical species having low mobility, which would limit the level of partitioning observed.

These results indicate that heterogeneity in slags as a result of the mobility of ions in the melt is a more dominant effect than heterogeneity resulting from the incomplete mixing of ores.

Isolated Crystals

In addition to the main types of phases observed in slags, several samples contained unusual crystals. The analyses of these are presented in Appendix 9.

The atypical dark dendrites in Taw River sample 2/15 were surrounded by very tiny pale specks. Analysis showed these to be composed mainly of ZrO_2 with TiO_2 and SnO. There is also some SiO_2, Al_2O_3, FeO and WO_3 present. Owing to the very small size of these spots, it is probable that there is some interference from the adjacent matrix and feather phases, so it is possible that the dominant element in the spots is ZrO_2 as this does not occur in any great quantity in either of those phases. SnO and WO_3 are also more abundant than in the adjacent phases.

In the early slags from Caerloggas and Crift Farm, rare clusters of dark crystals formed into a ring were observed, the very small component crystals being either sub-cubic or needle-like. It is probable that there is some interference from the underlying matrix and there is apparently some variation in composition between the crystals analysed.

Both types of dark crystal in the Caerloggas samples appear to contain Al_2O_3, SiO_2, FeO and most also have SnO, but only vague trends in the levels of these elements are discernible: FeO appears to be higher in the rectangular crystals, while Al_2O_3 is higher in the dark needles. In addition, when the minor elements are considered, it can be seen that the rectangular crystals all have enhanced MgO, some being extremely high, up to 17%, whereas MgO is not enhanced in the needle-like crystals.

At the centre of the ring, the slag is almost wholly Al_2O_3 with some SiO_2 and SnO.

The dark crystals in the Crift Farm sample appear to have more variable compositions. One of the needles has very high Al_2O_3 with some SiO_2 and SnO (thus showing the same trends as the Caerloggas needles), but the other is almost wholly Al_2O_3. One rectangular crystal contains high SiO_2 with some Al_2O_3, FeO and SnO; the other contains only very high Al_2O_3 with some SiO_2.

In addition to the dark crystal rings, pale crystals were also seen in the Caerloggas slag. These are almost entirely composed of tin oxide, and it is probable that these are either unreduced or re-precipitated crystals of cassiterite.

Isolated pale crystals were also observed in the blowing house slag from Week Ford, but these are not SnO. The compositions of the two crystals analysed are apparently somewhat different: one is ZrO_2 with moderate SiO_2, i.e. zirconia; the other is moderate SiO_2 and Al_2O_3 with some TiO_2, FeO and SnO, plus the majority of the MoO_3.

3.1.4.3: Analysis of Mineral Inclusions

The results of the chemical analysis of residual mineral crystals that survived the smelting process are presented in Table 3.9. The most common inclusion present in the slags (15 of the 25 analyses) has a composition that is mainly SiO_2; this is probably quartz. Six inclusions contain ZrO_2 with SiO_2. This suggests that the inclusion is a crystal of zircon ($ZrSiO_4$). The relative molecular masses of silicon (28) and zirconium (98) expressed as the oxides would give percentages of 32.6 and 67.3 respectively, close to the values obtained. Three inclusions are composed of a mixture of chemical species including Na_2O, Al_2O_3, SiO_2 and K_2O, which suggest that they are crystals of alkali feldspar. Three of the samples have both sodium and potassium present and the crystals may therefore be solid solutions of orthoclase ($KAlSi_3O_8$) and albite ($NaAlSi_3O_8$). A 50% solid solution of these two minerals would generate the following percentages: Na_2O = 8.6%, Al_2O_3 = 28.3%, SiO_2 = 50% and K_2O= 13%. The data do show some deviation from this. The samples from Gobbett and Wapsworthy are richer in sodium; the sample from Drakeford Bridge is richer in Potassium.

One sample contains Na_2O, MgO, Al_2O_3 and SiO_2, and may therefore be a crystal of mica (general formula $KMg_3(AlSi_3O_{10})(OH)_2$).

Table 3.9: Chemical Composition of Mineral Inclusions (wt%)

Oxide	Avon Dam 2/20	Ditsworthy 3/01	Doe Tor Green 2/12 (1)	Doe Tor Green 2/12 (2)	Drakeford Bridge 2/19	Eylesbarrow 4/06	Gobbett 2/28	U Merrivale 2/25	U Merrivale 2/32	U Merrivale 2/57	Nosworthy 3/16	Nosworthy 3/17	Retallack 4/02	Riddon 2/39	South Hill I 2/43 (1)	South Hill I 2/43 (2)	South Hill I 2/43 (3)	Taw River 2/40	Taw River 2/41	Teignhead Farm 2/14	Wapsworthy 2/29 (1)	Wapsworthy 2/29 (2)	Wapsworthy 2/29 (3)	Lower Yealm Steps 3/32	Yellowmead 2/44
Na_2O	1.5	1.6	1.7	1.7	3.7	1.9	8.1	1.8	1.0	2.2	1.9	1.1	2.0	0.9	0.8	2.1	1.9	1.1	0.9	1.3	1.7	6.1	1.7	2.4	8.6
MgO	0.4	0.3	0.2	0.3	0.1	0.3	nd	0.2	0.5	0.3	0.3	0.1	0.4	0.2	0.3	0.4	0.2	0.6	0.4	0.5	0.2	0.3	0.2	0.4	6.8
Al_2O_3	1.8	nd	0.1	nd	19.8	nd	26.8	nd	0.1	0.6	nd	0.1	nd	nd	nd	3.0	2.3	nd	nd	nd	0.4	19.5	0.5	0.7	24.1
SiO_2	96.4	99.9	99.1	100.5	61.0	99.9	60.2	99.9	30.1	98.0	97.6	99.7	98.6	30.5	29.9	89.0	95.7	32.0	30.7	31.2	98.6	64.4	97.2	95.5	49.6
P_2O_5	0.2	nd	nd	nd	0.1	nd	nd	nd	1.2	0.3	nd	nd	nd	0.2	0.2	nd	nd	1.1	0.9	0.6	nd	nd	nd	nd	0.6
K_2O	0.2	nd	nd	nd	12.5	nd	4.8	nd	nd	nd	nd	nd	nd	0.1	nd	1.7	1.4	nd	nd	nd	nd	9.8	nd	0.3	1.6
CaO	nd	nd	nd	nd	0.6	nd	0.6	nd	nd	nd	0.2	nd	0.3	nd	nd	0.1	nd	0.1	nd	nd	nd	0.3	nd	nd	0.5
TiO_2	0.2	nd	nd	nd	0.5	0.1	0.1	nd	1.0	nd	0.1	nd	nd	nd	nd	0.8	0.1	0.3	0.2	0.1	0.2	nd	0.3	0.2	1.5
V_2O_5	nd	nd	nd	nd	nd	0.1	nd	nd	nd	nd	0.1	nd	nd	nd	0.1	nd	nd	0.1	0.1	nd	nd	nd	nd	nd	nd
MnO	nd	nd	nd	nd	0.1	nd	nd	nd	0.1	nd	nd	0.1	nd	nd	nd	0.1	nd	0.1	nd	nd	nd	0.1	0.1	0.1	0.4
FeO	0.5	0.1	0.1	0.1	1.8	0.1	0.8	0.1	0.9	0.2	0.2	nd	nd	0.1	0.1	2.0	0.1	0.8	0.2	0.3	0.2	0.8	0.4	0.5	1.2
CuO	nd	nd	0.1	nd	nd	0.1	nd	nd	nd	nd	nd	0.1	nd	nd	nd	nd	0.1	nd	nd	nd	nd	nd	0.1	nd	nd
ZnO	nd	nd	nd	nd	nd	0.1	nd	nd	0.1	0.1	0.1	0.1	0.2	0.1	nd	0.1	nd	nd	nd	nd	nd	nd	nd	0.1	nd
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	nd	nd	nd	nd	nd	nd	nd	nd	64.6	nd	nd	nd	nd	70.4	70.0	nd	nd	71.8	69.6	72.5	nd	nd	nd	nd	2.1
MoO_3	0.5	0.1	nd	nd	0.2	nd	0.2	0.2	nd	0.4	0.1	nd	0.3	nd	nd	0.4	0.3	nd	nd	nd	0.1	0.1	0.2	0.1	0.4
SnO	1.1	0.4	0.3	0.2	1.2	0.2	0.1	0.1	1.1	0.4	0.4	0.2	0.2	nd	nd	1.4	nd	1.3	nd	nd	0.8	0.2	1.3	1.4	5.2
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
WO_3	nd	nd	0.5	nd	nd	nd	0.1	nd	0.9	0.2	0.6	0.6	0.5	nd	0.8	0.1	nd	0.8	0.6	0.1	nd	0.2	nd	0.1	nd
Sum	102.7	102.3	102.1	102.8	101.5	102.6	101.7	102.2	101.6	102.8	101.5	102.1	102.5	102.5	102.5	101.2	102.0	110.2	103.6	106.7	102.0	101.8	101.9	101.9	102.7

nd = not detected KEY: Quartz Alkali feldspar Zirconia Mica?

Few samples contained more than one inclusion large enough to permit analysis, but of those that did, sample 2/43 from South Hill and sample 2/29 from Wapsworthy both contained more than one different type of inclusion.

3.1.4.4: Analysis of Metallic Prills

Table 3.10 and Figure 3.42 show the results of the analysis of individual metallic prills trapped within the slag matrix. Fifty-five samples contained prills large enough to permit analysis, and from these 31 provided data for multiple prills.

Table 3.10: Chemical Composition of Metallic Prills (wt%)

Element	Avon Dam 2/20			Butterbrook 2/33			Butterbrook 2/34
	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2	Prill 3	Prill 1
Mn	nd	nd	nd	nd	nd	0.1	0.2
Fe	0.9	0.3	0.3	1.4	0.2	0.2	10.5
Cu	nd	nd	nd	nd	nd	nd	nd
Zn	nd	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd	nd
Mo	nd	0.1	nd	0.4	nd	nd	1.3
Sn	100.3	100.9	101.0	97.4	101.9	101.4	82.2
Sb	nd	nd	nd	nd	nd	nd	nd
W	nd	nd	nd	1.6	nd	nd	8.1
Sum	101.2	101.2	101.3	99.1	102.0	101.6	94.2

Element	Caerloggas 3/44			Caerloggas 3/45		Carvedras 3/30	
	Prill 1	Prill 2	Prills 3	Prill 1	Prill 2	Prill 1	Prill 2
Mn	nd	nd	nd	nd	nd	nd	0.1
Fe	nd	nd	nd	0.1	0.1	0.4	1.0
Cu	0.1	nd	0.1	nd	nd	nd	0.1
Zn	nd	0.4	0.2	nd	0.1	nd	nd
As	nd	nd	nd	0.1	nd	nd	nd
Mo	nd	0.1	nd	nd	0.1	1.6	1.0
Sn	96.2	99.7	100.5	100.5	101.2	nd	2.6
Sb	nd	nd	nd	nd	nd	nd	0.2
W	nd	nd	0.1	0.1	0.3	99.6	96.2
Sum	96.4	100.2	100.9	100.7	101.7	101.6	101.1

Element	Crift Farm 4/15	Crift Farm 4/16		Crift Farm 4/17			Crift Farm 4/27	
	Prill 1	Prill 1	Prill 2	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2
Mn	nd	nd	0.1	nd	nd	nd	nd	nd
Fe	0.1	0.1	0.1	0.3	0.2	0.1	0.2	0.4
Cu	nd	0.1	0.2	nd	nd	nd	nd	nd
Zn	nd	0.1	0.1	nd	0.3	nd	nd	nd
As	nd	nd	nd	nd	nd	nd	nd	nd
Mo	nd	1.5	0.1	0.1	0.1	nd	nd	nd
Sn	99.3	97.9	98.9	101.0	95.4	103.2	102.6	97.2
Sb	0.2	0.1	nd	nd	nd	nd	nd	0.1
W	0.5	0.1	0.4	0.6	1.8	nd	nd	0.2
Sum	99.7	99.9	100.0	102.1	97.6	103.3	102.8	97.9

nd = not detected

Element	Ditsworthy 3/01	Doe Tor Green 2/12			Eylesbarrow 2/35	Eylesbarrow 4/06
	Prill 1	Prill 1	Prill 2	Prill 3	Prill 1	Prill 1
Mn	nd	0.1	nd	nd	nd	nd
Fe	nd	0.8	2.7	0.2	0.7	0.6
Cu	nd	nd	nd	nd	nd	nd
Zn	0.2	nd	nd	nd	nd	nd
As	0.1	nd	nd	0.1	nd	nd
Mo	0.1	1.0	0.9	nd	nd	0.1
Sn	99.8	41.0	56.7	99.9	100.2	99.3
Sb	nd	0.1	0.2	nd	nd	0.7
W	0.4	57.7	40.5	0.6	nd	nd
Sum	100.6	100.7	100.9	100.7	100.8	100.7

Element	Glazebrook 2/58	Gobbett 2/28		Hurdon 2/01	Hurdon 4/26	Lether Tor Farm 2/11		
	Prill 1	Prill 1	Prill 2	Prill 1	Prill 1	Prill 1	Prill 2	Prill 3
Mn	0.1	0.1	0.3	nd	nd	nd	nd	nd
Fe	0.4	0.4	6.8	0.1	0.1	nd	nd	nd
Cu	nd	nd	nd	nd	0.2	0.1	nd	0.1
Zn	0.1	nd	0.2	nd	nd	nd	nd	0.2
As	nd	nd	nd	nd	0.1	nd	nd	0.1
Mo	0.2	nd	nd	0.1	0.2	nd	nd	0.2
Sn	100.5	98.4	89.4	100.2	100.0	99.7	99.9	96.3
Sb	nd	nd	nd	nd	nd	-	-	-
W	0.5	0.5	0.2	0.2	nd	0.4	0.3	0.5
Sum	101.6	99.3	96.9	100.5	100.5	100.1	100.1	97.3

Element	Lingcombe 3/19	Longstone 2/06	Longstone 2/07	Longstone 4/24		Lower Merrivale 4/04		
	Prill 1	Prill 1	Prill 1	Prill 1	Prill 2	Prill 1	Prill 2	Prill 3
Mn	nd	nd	nd	0.2	0.1	0.1	0.1	0.1
Fe	0.2	nd	nd	nd	1.2	0.7	3.1	1.1
Cu	nd	0.1	0.1	nd	nd	0.3	nd	nd
Zn	nd	nd	nd	nd	nd	0.1	nd	0.1
As	nd	nd	nd	0.1	nd	nd	0.1	nd
Mo	0.1	0.2	nd	0.1	nd	0.4	0.6	0.3
Sn	100.8	100.3	101.4	100.0	99.9	98.5	97.0	97.1
Sb	nd	nd	nd	nd	nd	nd	nd	0.8
W	nd	0.1	0.1	nd	nd	0.4	0.2	0.4
Sum	101.2	100.6	101.5	100.3	101.2	100.5	101.2	100.0

Element	Lower Merrivale 4/28		Upper Merrivale 2/25	Upper Merrivale 2/31	Upper Merrivale 2/32	Upper Merrivale 2/52	Upper Merrivale 2/57
	Prill 1	Prill 2	Prill 1	Prill 1	Prill 1	Prill 1	Prill 1
Mn	nd	nd	0.1	nd	nd	0.3	nd
Fe	0.8	0.5	nd	6.5	0.1	nd	0.2
Cu	0.2	0.1	nd	nd	nd	0.1	nd
Zn	nd	nd	nd	0.3	nd	nd	nd
As	nd	nd	nd	0.1	nd	nd	nd
Mo	0.1	0.1	nd	0.2	0.1	0.6	0.1
Sn	104.4	100.8	101.1	92.4	100.2	101.2	99.8
Sb	nd	nd	nd	nd	nd	nd	nd
W	nd	nd	nd	0.7	0.2	nd	0.5
Sum	105.5	101.4	101.2	100.2	100.5	102.1	100.7

Element	Upper Merrivale 3/24	Metherel 2/48		Metherel 2/49			Nosworthy 3/16	
	Prill 1	Prill 1	Prill 2	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2
Mn	0.1	0.1	0.1	nd	nd	nd	nd	0.1
Fe	nd	nd	nd	nd	nd	nd	0.4	2.2
Cu	0.1	nd	nd	nd	nd	nd	nd	0.2
Zn	nd	0.2	nd	0.2	0.2	nd	nd	0.2
As	0.1	0.1	0.2	0.1	nd	nd	nd	nd
Mo	0.1	nd	nd	nd	nd	0.3	0.4	0.3
Sn	101.5	99.4	99.3	94.7	98.9	100.8	99.3	94.5
Sb	nd	nd	nd	nd	nd	nd	0.2	nd
W	nd	0.2	0.3	nd	nd	nd	0.2	3.4
Sum	101.9	100.0	99.9	94.9	99.1	101.1	100.5	100.9

Element	Outer Down 4/18		Retallack 4/01			Retallack 4/02	
	Prill 1	Prill 2	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2
Mn	0.1	0.1	nd	0.1	nd	0.2	nd
Fe	0.8	0.1	nd	nd	nd	0.3	0.3
Cu	nd	0.3	nd	nd	nd	2.5	0.3
Zn	0.1	nd	nd	0.1	0.2	nd	nd
As	nd	nd	nd	nd	nd	nd	0.1
Mo	nd	0.1	nd	nd	0.1	2.1	0.2
Sn	98.5	100.2	101.1	100.4	101.6	95.6	98.7
Sb	0.3	nd	nd	nd	nd	nd	nd
W	0.1	nd	0.2	0.4	0.3	nd	0.4
Sum	99.7	100.7	101.2	100.9	102.2	100.6	100.0

Element	Retallack 4/03			Riddon 2/39	South Hill 2/43	Stannon Brook 4/25		
	Prill 1	Prill 2	Prill 3	Prill 1	Prill 1	Prill 1	Prill 2	Prill 3
Mn	nd	nd	0.1	0.2	0.1	nd	nd	0.2
Fe	0.3	nd	0.1	2.7	15.8	16.7	2.9	0.6
Cu	nd	nd	0.1	0.1	nd	0.2	nd	0.1
Zn	nd	nd	0.1	nd	0.1	nd	nd	nd
As	0.1	0.2	0.1	nd	nd	nd	0.2	0.1
Mo	0.4	0.1	nd	0.4	0.1	nd	nd	0.2
Sn	100.5	104.4	95.7	98.0	85.2	83.9	97.5	99.3
Sb	nd	nd	nd	nd	nd	nd	nd	nd
W	nd	nd	0.1	0.2	0.1	nd	nd	0.1
Sum	101.3	104.7	96.3	101.7	101.4	100.6	100.7	100.5

Element	Taw River 2/15		Taw River 2/41	
	Prill 1	Prill 2	Prill 1	Prill 2
Mn	nd	0.1	0.1	nd
Fe	0.1	0.1	0.7	0.2
Cu	0.1	nd	0.1	0.1
Zn	0.1	0.2	0.1	nd
As	0.1	0.1	0.2	0.1
Mo	0.1	0.1	0.1	0.2
Sn	94.6	103.6	100.0	100.3
Sb	nd	0.1	nd	nd
W	0.2	nd	0.2	nd
Sum	95.2	104.2	101.4	100.8

Element	Trereife 3/35						Trereife 3/36
	Prill 1			Prill 2			Prill 1
	light	dark	mid	light	dark	mid	
Mn	0.1	nd	nd	nd	0.1	0.1	nd
Fe	nd	39.5	0.2	nd	39.4	nd	0.2
Cu	0.1	0.2	36.5	nd	nd	0.1	nd
Zn	nd	nd	nd	nd	nd	nd	nd
As	nd	57.8	0.1	0.5	58.7	30.8	0.4
Mo	nd	2.1	nd	nd	1.8	0.3	0.3
Sn	96.1	1.0	63.3	101.0	0.7	69.3	99.5
Sb	nd	0.1	nd	nd	nd	nd	nd
W	nd	nd	0.2	nd	nd	0.2	0.3
Sum	96.2	100.7	100.3	101.6	100.7	100.7	100.7

Element	Trevellas Porth 4/19		Wallabrook 3/18			Wapsworthy 2/29	
	Prill 1	Prill 2	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2
Mn	0.1	0.1	0.3	0.1	0.3	nd	0.2
Fe	0.1	0.8	15.5	0.3	3.3	0.1	0.2
Cu	nd	0.1	nd	0.1	0.3	0.1	nd
Zn	nd	nd	nd	nd	0.1	nd	nd
As	0.2	nd	nd	nd	nd	nd	nd
Mo	nd	0.2	1.9	0.5	0.4	nd	0.1
Sn	100.8	99.7	74.7	95.6	96.2	101.2	100.7
Sb	nd	nd	nd	0.2	nd	nd	nd
W	nd	nd	8.7	nd	0.3	nd	nd
Sum	101.2	100.8	101.0	96.7	101.0	101.5	101.2

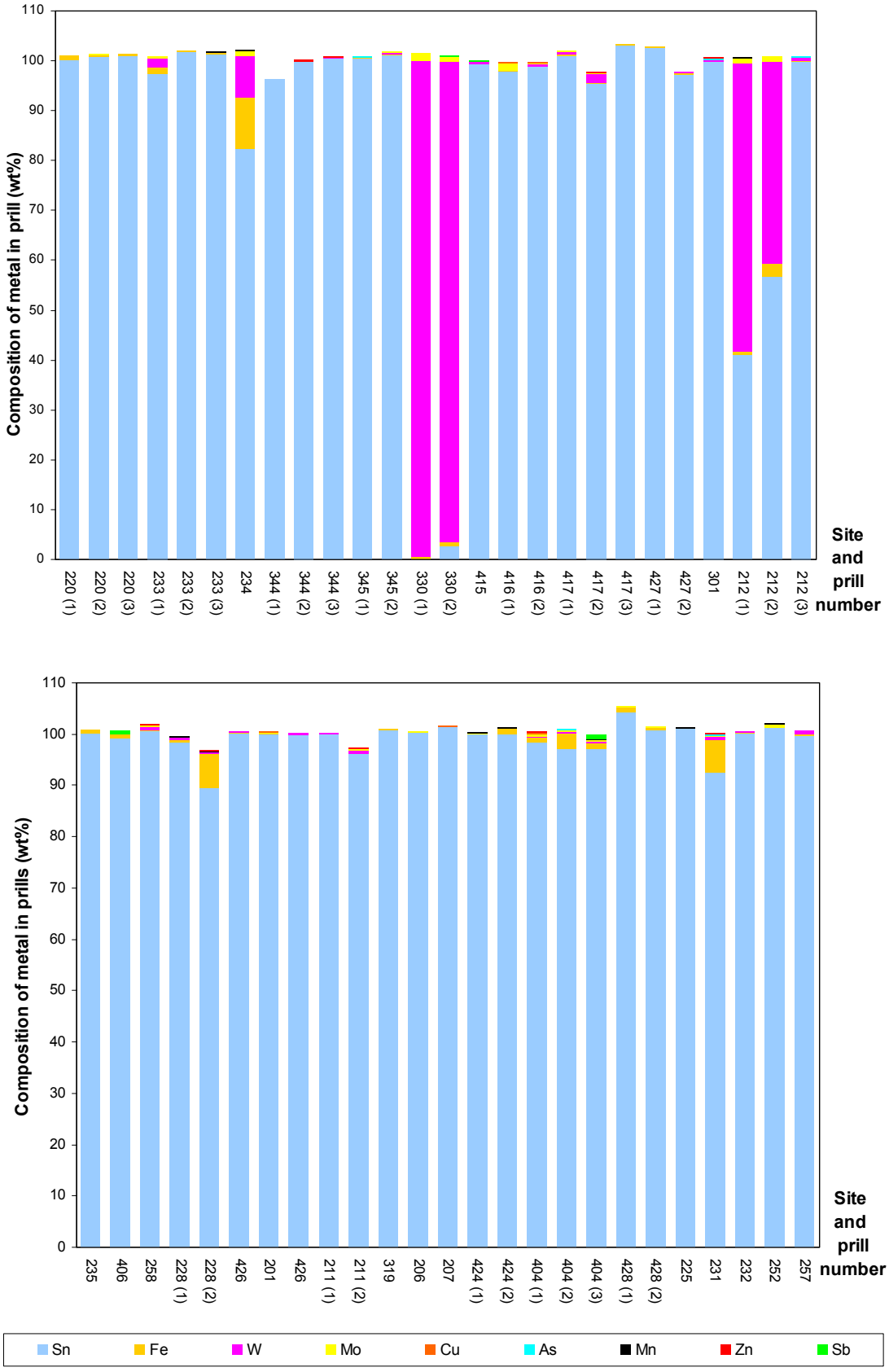
Element	Week Ford 4/23			Lower Yealm Steps 2/13	
	Prill 1	Prill 2	Prill 3	Prill 1	Prill 2
Mn	nd	nd	0.1	nd	0.1
Fe	0.3	0.3	nd	0.4	0.8
Cu	0.2	0.1	0.1	nd	nd
Zn	nd	0.1	nd	0.3	nd
As	nd	nd	nd	nd	nd
Mo	0.1	0.1	0.1	0.2	nd
Sn	99.7	99.6	100.6	98.6	98.6
Sb	nd	nd	nd	nd	0.6
W	nd	nd	nd	0.6	0.1
Sum	100.4	100.2	100.9	100.0	100.2

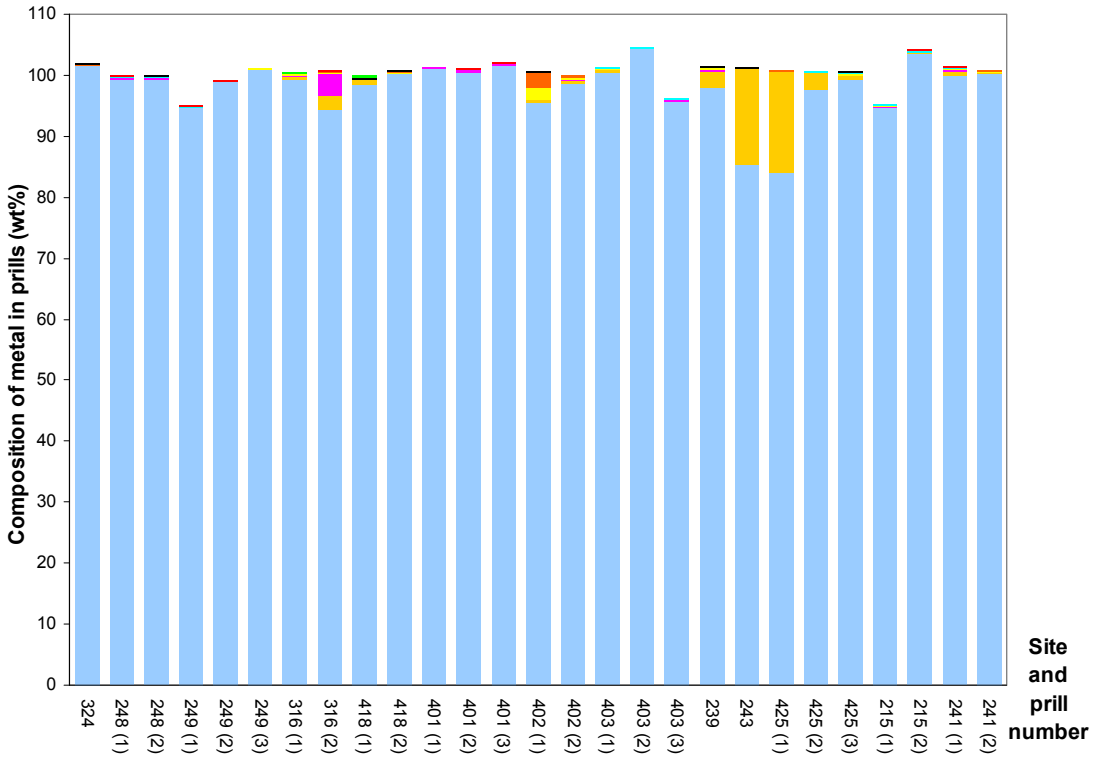
Element	Lower Yealm Steps 3/31			Lower Yealm Steps 3/32	Upper Yealm Steps 2/10	Yellowmead 2/44	Yes Tor Bottom 2/60
	Prill 1	Prill 2	Prill 3	Prill 1	Prill 1	Prill 1	Prill 1
Mn	nd	nd	nd	nd	nd	0.1	nd
Fe	nd	nd	0.1	0.1	nd	0.3	nd
Cu	nd	0.1	0.1	nd	nd	nd	0.2
Zn	0.3	nd	0.2	nd	nd	0.3	nd
As	nd	nd	nd	0.1	nd	nd	nd
Mo	0.2	0.1	0.1	0.1	0.1	0.1	nd
Sn	99.2	99.9	99.7	100.2	100.4	100.1	101.0
Sb	0.2	nd	nd	nd	nd	nd	nd
W	0.2	0.1	0.4	0.2	0.2	nd	nd
Sum	99.9	100.2	100.6	100.6	100.7	100.9	101.2

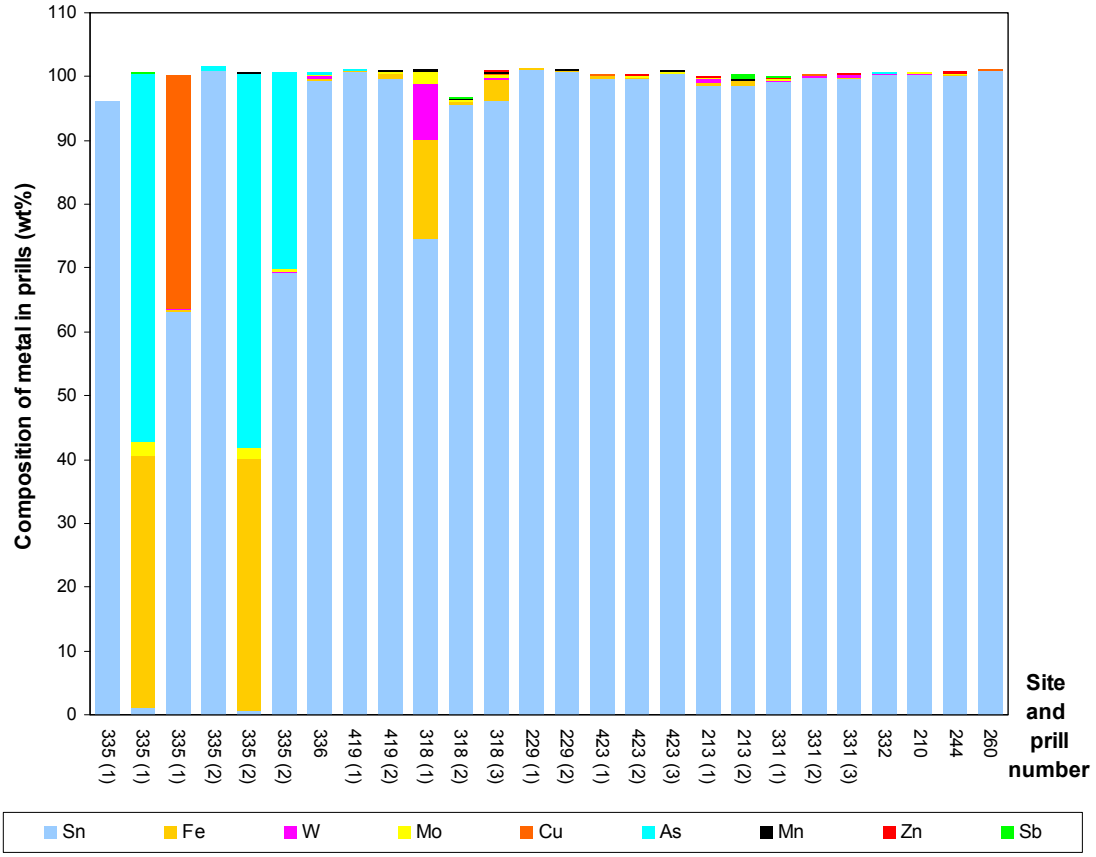
Although prills of pure tin occur relatively frequently (of the 104 prills analysed, 79 were tin with other elements each present at less than 1% concentration by weight) the data indicates that metallic prills can have a wide variety of compositions. This variation is not limited to prills in slags from different sites: a single piece of slag may contain several prills each of quite different composition. Of the 31 samples with multiple prills available for analysis, 12 had prills of different compositions.

Individual samples from the following sites were found to contain only prills of pure tin: Avon Dam, Caerloggas, Crift Farm (2 of 4 samples), Ditsworthy, Eylesbarrow, Glazebrook, Hurdon, Lether Tor Farm, Lingcombe, Longstone (2 of 3 samples), Lower Merrivale (1 of 2 samples), Upper Merrivale (5 of 6 samples), Metherel, Outer Down, Retallack (2 of 3 samples), Taw River, Trereife (1 of 2 samples) Trevellas Porth, Wapsworthy, Week Ford, Lower Yealm Steps, Upper Yealm Steps, Yellowmead and Yes Tor Bottom.

Figure 3.42: Chemical Composition of Metallic Prills




Composition of metal in prills (wt%)
110
100
90
80
70
60
50
40
30
20
10
0
324
248 (1)
248 (2)
249 (1)
249 (2)
249 (3)
316 (1)
316 (2)
418 (1)
418 (2)
401 (1)
401 (2)
401 (3)
402 (1)
402 (2)
403 (1)
403 (2)
403 (3)
239
243
425 (1)
425 (2)
425 (3)
215 (1)
215 (2)
241 (1)
241 (2)
Site and prill number


Composition of metal in prills (wt%)
110
100
90
80
70
60
50
40
30
20
10
0
335 (1)
335 (1)
335 (1)
335 (2)
335 (2)
335 (2)
336
419 (1)
419 (2)
318 (1)
318 (2)
318 (3)
229 (1)
229 (2)
423 (1)
423 (2)
423 (3)
213 (1)
213 (2)
331 (1)
331 (2)
331 (3)
332
210
244
260
Site and prill number
Sn
Fe
W
Mo
Cu
As
Mn
Zn
Sb

The most common metallic elements occurring in the remaining samples are iron and tungsten. Whenever iron occurs, it is always with tin, and is present in concentrations up to 16.7% in blowing house slags and 39.5% in reverberatory slags. Examples of simple tin/iron prills (although other prills in these samples are pure tin) are found in samples from Longstone, Lower Merrivale, Upper Merrivale, Riddon, South Hill, Stannon Brook and Wallabrook. The occurrence of tungsten in prills, though not common, is somewhat more complex. It is almost always associated with tin, either with or without iron and/or molybdenum being present. In most cases it is present at levels <10% (e.g. in samples from Butterbrook, Crift Farm, Nosworthy and Wallabrook). Tungsten levels in the range 40-60% are found in the prills of the Doe Tor Green slag. Prills composed of tungsten >95% (accompanied by minor molybdenum, with or without tin and iron) occur in the reverberatory slag from Carvedras.

More unusual combinations of elements also occur. In one prill in one of the samples from Retallack the tin is contaminated by minor molybdenum and copper. The samples from Trereife contain very varied prills, including tin with minor molybdenum, tin with copper, and arsenic associated with tin and/or iron and minor molybdenum. This is the only site with prills containing arsenic.

It was noted previously (Table 3.1) that some prills had a mottled appearance or an irregular shape. Mottling is a potential indicator of the presence of patches of two or more different metals or alloys within a prill: for example a tin prill might contain patches of the intermetallic tin-iron compound known as hardhead (Figure 3.43), which would appear darker than the surrounding tin when viewed using backscattered SEM imaging. The presence together in a prill of two metals that are mutually insoluble

could cause the prill to fail to coalesce, thus it would have an irregular shape rather than be spherical. For a discussion of the behaviour of iron, tungsten and arsenic in tin see Section 4.1.2.3.

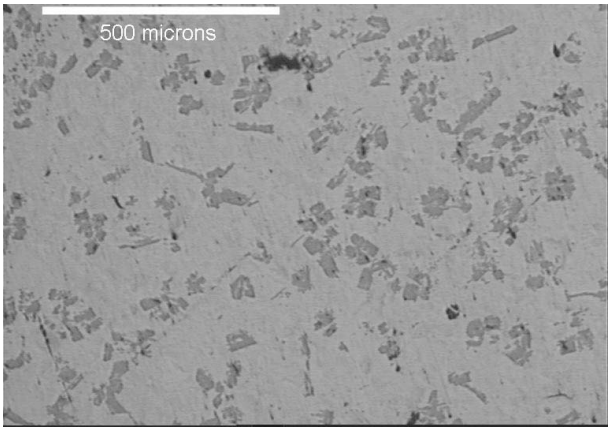


Figure 3.43: Microstructure of a piece of Metallic Tin with 2% Iron content, showing dark crystals of the Intermetallic Tin-Iron Compound Hardhead (probably $FeSn_2$) in a Matrix of Tin Metal

Table 3.11 shows the relationship between the compositions of prills and the occurrence of mottling and irregularity. It demonstrates that these features are often associated with prills containing metals other than tin. There are exceptions, however. In particular, samples containing only low levels of iron (<3%) (e.g. Longstone, Lower Merrivale, Riddon) tend to have prills with no unusual characteristics, but even for samples with prills containing relatively high proportions of other elements (e.g. Upper Merrivale (2/31), Stannon Brook, Wallabrook) there might be no observable effect upon the appearance of the prills.

Conversely, some samples that do exhibit these features appear to have prills composed only of pure tin (e.g. Retallack 4/01, Trereife 3/36, Trevellas Porth). It is likely, based on analysis of other material from Trevellas Porth that non-tin prills do occur in this slag but have not been analysed owing to their small size. (For an analysis of the metal

Table 3.11: The Compositions of Mottled and Irregular Shaped Prills

Sample	Irregular shape	Mottling	Iron (wt%)	Tungsten (wt%)	Arsenic (wt%)
Butterbrook 2/33	✓		1.6 - -	1.4 - -	- - -
Butterbrook 2/34	✓		10.5	8.1	-
Carvedras 3/30	✓		- 1.0	99.6 96.2	- -
Charlestown	✓		Prills not analysed		
Crift Farm 4/17			- - -	- 1.8 -	- - -
Doe Tor Green 2/12		✓	- 2.7 -	57.7 40.5 -	- - -
Eylesbarrow 4/06	✓		-	-	-
Gobbett 2/28			- 6.8	- -	- -
Longstone 4/24			- 1.2	- -	- -
L. Merrivale 4/04			- 3.1 1.1	- - -	- - -
U. Merrivale 2/21	✓		Prills not analysed		
U. Merrivale 2/31			6.5	-	-
Nosworthy 3/16	✓	✓	- 2.2	- 3.4	- -
Retallack 4/01		✓	-	-	-
Riddon			2.7	-	-
South Hill			15.8	-	-
Stannon Brook			16.7 2.9 -	- - -	- - -
Trereife 3/35	✓	✓	39.5 39.4	- -	57.8 58.7
Trereife 3/36	✓	✓	-	-	-
Trevellas Porth	✓		-	-	-
Wallabrook			15.5 3.3 -	8.7 - -	- - -

samples from Trevellas Porth see Section 3.4.3). The same is probably true for sample 4/01 from Retallack and 3/36 from Trereife. While all the prills visible in a sample

were considered when noting whether there was mottling or irregularity, only the largest prills were subjected to compositional analysis, thus it is possible that some of the samples may only have had spherical prills analysed.

3.1.5: Investigation of Melting Range and Viscous Behaviour

The melting behaviour of slag was examined using slag from Upper Merrivale. Two samples with different physical characteristics were selected for the experiment: one from Context 798 with large areas of glassy matrix and only a few isolated feathery phases present; the other from Context 773 which was wholly dendritic (see Figures 3.44 a and b). The samples selected were sufficiently large so that each could be divided into two parts: a control sample to be mounted and polished without being subjected to any heating so that the original microstructure and composition could be determined (analysis of these slags has been presented in Section 3.1.4.1: the glassy slag as sample 3/24 and the dendritic slag as sample 3/27); and a sample to be heated stepwise to establish the melting range of the slag.

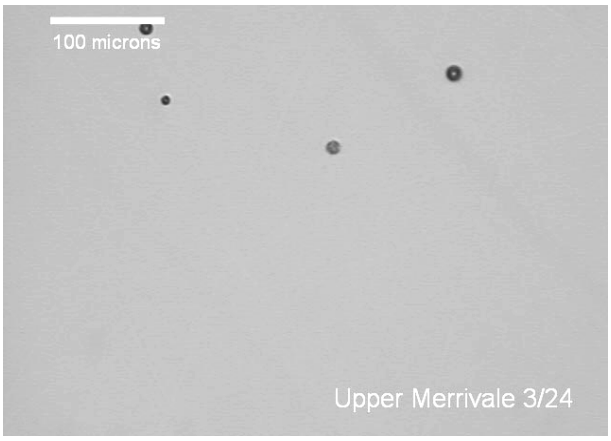


Figure 3.44a: Sample 3/24: Glassy Slag

The samples to be heated were placed at the bottom of separate clay/graphite crucibles, into which was placed one substantial piece of charcoal, with smaller pieces deposited on top, so that the mouth of the crucible was filled and a reducing atmosphere would be generated within the crucible, but without any of the charcoal coming into contact with the molten slag and becoming mixed in with it.

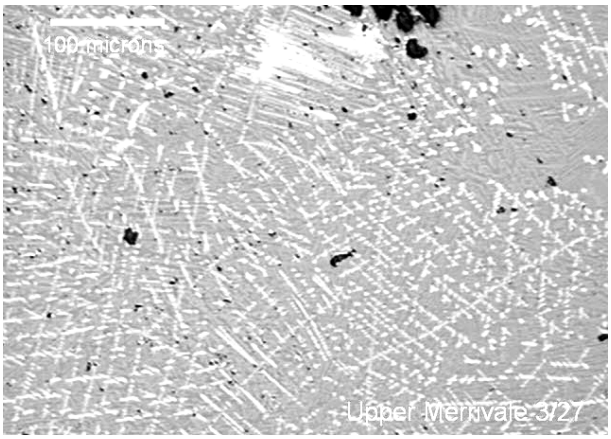


Figure 3.44b: Sample 3/27: Dendritic Slag, showing iron silicate dominated dark matrix, with fine pale titanium-rich dendrites and mid-grey tin and tungsten-enriched crystal laths distributed over entire surface of sample

The two crucibles were placed into the furnace and the samples heated for 30 minutes at a temperature of 1000 °C. After this time, each crucible was quickly removed from the furnace and the blocks of charcoal lifted away so that any changes to the state of the sample within could be noted. Tongs were used to check if the samples were softening. The charcoal was then replaced and the crucibles returned to the furnace. The temperature of the furnace was raised in increments of 50°C to a maximum of 1150°C, a time of 30 minutes being allowed between each examination of the samples. Results are presented in Table 3.12, which includes for comparison the results of a similar study of slag from Crift Farm (Malham 1996 p53).

The investigation showed that the glassy slags from both Upper Merrivale and Crift Farm began to melt at a comparatively low temperature; however, they were extremely viscous and remained so even when the temperature was raised by 100°C. By contrast, the dendritic slag began melting at a temperature approximately 50°C higher, but thereafter became very much more fluid as the temperature increased.

A final examination of the slag from Upper Merrivale revealed that a small quantity of metallic tin had collected at the bottom of the crucible, having been lost from the slag during heating.

Table 3.12: Melting Range and Viscous Behaviour of Slags

Temp/°C	Upper Merrivale Glassy Slag	Upper Merrivale Dendritic Slag	Crift Farm Glassy Slag
1000	Slumped to bottom of crucible and could be indented with effort.	Not altered shape.	Deformation under own weight; would not pour.
1050	Slumped to bottom of crucible and could be indented; would not pour.	Not altered shape but could be indented.	Deformation under own weight; pours with extreme difficulty.
1100	Slumped to bottom of crucible and could be indented; slightly runnier but would not pour.	Runny and capable of being poured; consistency of ketchup.	Marked deformation under own weight; pours slowly.
1150	Slumped to bottom of crucible and could be indented; slightly runnier but would not pour.	Very fluid; runnier than golden syrup.	-

3.2: Results of Ore Analysis

3.2.1: Description of Ore Samples

Physical characteristics of the ore samples are recorded in Table 3.13. Images of the samples are presented in the Image Gallery, File 3 (see CD-ROM).

Table 3.13: Description of Tin Ore Samples

Site	Sample No	Mass (g)	Size (cm)	Description
Caerloggas	4/12	15.3	2.0 x 1.5 x 1.0	Part of a sub-rectangular cassiterite pebble. The uncut surfaces are weathered smooth, and are a mottled dark grey. The cut surfaces show irregular approx. 2mm wide alternating bands of a dark blue/grey mineral and a dark grey/brown mineral, both with a sub-mm crystal size. The sample is non-magnetic.
Caerloggas	4/13	100.5	3.5 x 4.0 x 2.0	A sub-cylindrical pebble with a smooth weathered surface appearing to consist of grey/black crystals, interspersed with pale brown crystals. Crystal size up to 2mm. The freshly exposed surface shows grey/black crystals with a glassy lustre, interspersed with white crystals – the pale brown of the exterior thus being staining. The sample is non-magnetic.
Chysauster	4/30	250.0	4.0 x 5.0 x 4.0	A sub-spherical pebble with a flat base. The dark grey/black surface is weathered smooth. Exposed surfaces consist of black crystals with a glassy lustre, interspersed with plentiful quartz crystals. Crystal size up to 3mm. Two extremely narrow white (quartz?) veins are visible. The sample is non-magnetic.
Crift Farm	4/11	106.2	4.0 x 4.0 x 3.0	A sub-rectangular fragment of dark grey rock with no crystals individually distinguishable to the naked eye. The surface is weathered to a darker grey with some maroon mottling.

Dean Moor	3/48	Not recorded	4.0 x 4.5 x 2.5	The sample is a purplish-brown well-rounded pebble, which appears lighter where the interior has been exposed by the removal of a portion of the sample in the 1950s. Examination with a hand lens reveals that it is composed of crystals in the 500 μm range. A black mineral accounts for approximately half of the rock. This is mostly in the form of angular crystals with a glassy lustre, however some dull black/grey areas are visible. The majority of the rest of the rock is comprised of dark red crystals, also glassy. Occasional clear quartz crystals (>1mm) can be seen.
Upper Merrivale	4/10	308	11.5 x 5.0 x 3.5	Unweathered wedge-shaped rock fragment, the bulk of which is pale grey in colour with no crystals individually distinguishable to the naked eye. Larger crystals of quartz, and bands of quartz run through the rock The sample is non-magnetic. (Flecks of red and yellow on the surface are lichen.).
Metherel	4/14	47.3	4.0 x 3.5 x 2.0	An irregular dull dark grey/black pebble composed of crystals just distinguishable to the naked eye. A 5mm thick vein of larger c.2mm shiny black, elongated crystals bisects the sample. Quartz crystals, accounting for less than 10% of the rock, are visible, including one 1mm x 18mm vein.

The majority of the samples are examples of alluvial ‘stream tin’ which were recovered from prehistoric sites, and have been identified as such owing to the fact that they all exhibit some degree of rounding, as would be caused by the action of water. However, there was also one piece from Crift Farm, which may be mined ore, and a sample of definite vein material selected from the extensive waste dumps at Upper Merrivale, both of which are angular and show none of the same abrasion of their surfaces.

The colour of the samples ranges from black through grey to dark red/brown, and it is striking just how different each of the samples appears.

Optical microscope images, taken to determine crystal size, are presented in the Image Gallery, File 4. Although some of the samples from prehistoric sites contain visible black/grey crystals, not all do, and thus the recognition of cassiterite was probably not accomplished by sight alone.

3.2.2: Chemical Analysis of Ore Samples

Scanning Electron Microscopy

The scanning electron microscope was used to determine the chemical composition of the bulk of each sample, and then of the individual mineral crystals within. Note that as tin would be present in ores in fully oxidized form, tin content is here calculated as SnO_2, rather than SnO as it was for slag analysis. Tables 3.14 to 3.19 contain compositional data and details of the magnification used for each scan.

An attempt has been made to identify particular mineral species based on these data, however the suggestions in some cases are very uncertain.

Both samples from Caerloggas are rich in tin: the larger sample (4/13) being comprised of approximately 60% cassiterite, the smaller sample (4/12) around 30%. Sample 4/12 also contains crystals composed of aluminium, silicon and iron, plus a small amount of sodium. These crystals may be iron-rich biotite mica, although potassium would be expected rather than sodium. Sample 4/13 is similar, but iron appears to be present only at trace levels. Crystal 2 may thus be feldspar.

Table 3.14: Chemical Composition of Caerloggas Ore Sample 4/12 determined by EDX-SEM (wt%)

	Bulk Analyses				Individual Crystals			
Oxide	**Area 1**	**Area 2**	**Area 3**	**Mean**	**1**	**2**	**3**	**4**
Na_2O	2.7	2.9	3.0	2.8	0.1	4.5	0.7	5.1
MgO	0.1	0.2	0.4	0.2	nd	0.1	0.1	nd
Al_2O_3	27.9	29.2	33.1	30.0	0.4	40.9	1.1	41.1
SiO_2	21.6	22.4	26.5	23.5	0.6	36.5	0.9	37.7
P_2O_5	nd	0.2	0.2	0.2	nd	0.1	nd	nd
K_2O	nd	nd	nd	nd	nd	nd	nd	0.1
CaO	0.5	0.3	0.2	0.3	0.9	0.2	0.9	0.1
TiO_2	0.2	nd	0.1	0.1	0.2	0.1	0.1	nd
V_2O_5	nd	0.1	nd	0.1	nd	nd	0.1	0.1
MnO	0.1	0.1	0.1	0.1	nd	0.3	nd	0.3
FeO	9.9	9.8	12.2	10.6	0.3	16.5	0.3	16.1
CuO	0.1	0.1	0.1	0.1	nd	nd	nd	nd
ZnO	0.2	0.1	0.3	0.2	0.1	0.1	nd	0.3
As_2O_3	nd	nd	nd	nd	0.3	nd	0.2	nd
ZrO_2	nd	nd	nd	nd	nd	nd	0.1	nd
MoO_3	0.2	nd	0.1	0.1	0.1	nd	0.1	nd
SnO_2	37.7	35.6	25.5	32.9	96.0	4.0	94.3	0.4
Sb_2O_3	0.2	0.1	0.2	0.2	0.7	nd	1.3	0.1
WO_3	nd	0.5	0.2	0.2	0.6	nd	nd	0.1
Sum	101.3	101.5	101.9	101.7	100.4	103.2	100.3	101.6
Scan mag	x 50	x 200	x 500		x 1000	x 1000	x 1000	x 1000

nd = not detected

Table 3.15: Chemical Composition of Caerloggas Ore Sample 4/13 determined by EDX-SEM (wt%)

	Bulk Analyses				Individual Crystals	
Oxide	**Area 1**	**Area 2**	**Area 3**	**Mean**	**1**	**2**
Na_2O	1.0	0.9	1.3	1.0	1.0	3.0
MgO	0.2	0.2	0.2	0.2	0.1	nd
Al_2O_3	31.4	24.5	30.0	28.6	0.3	63.3
SiO_2	11.8	8.7	11.4	10.6	0.7	35.6
P_2O_5	0.1	nd	nd	0.1	nd	0.3
K_2O	nd	nd	nd	nd	nd	nd
CaO	0.4	0.5	0.8	0.5	0.7	0.2
TiO_2	0.1	0.1	0.1	0.1	0.2	0.1
V_2O_5	nd	0.1	0.2	0.1	nd	0.1
MnO	0.2	nd	0.1	0.1	nd	nd
FeO	0.1	0.3	0.1	0.2	0.2	0.1
CuO	nd	nd	nd	nd	nd	0.2
ZnO	nd	nd	nd	nd	nd	nd
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	nd	nd	0.1	0.1	0.2	nd
MoO_3	nd	0.3	0.1	0.1	0.1	nd
SnO_2	60.1	68.3	55.7	61.3	96.1	0.1
Sb_2O_3	0.7	0.2	0.7	0.6	0.7	0.1
WO_3	nd	0.1	0.5	0.2	0.9	nd
Sum	106.0	104.2	101.1	103.9	101.0	102.9
Scan mag	x 100	x 100	x 100		x 1000	x 1000

Table 3.16: Chemical composition of Crift Farm Ore Sample 4/11 determined by EDX-SEM (wt%)

Oxide	Bulk	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot 6
Na_2O	1.1	0.4	5.2	0.5	1.9	0.3	2.4
MgO	0.3	nd	0.8	nd	0.5	0.7	1.8
Al_2O_3	6.2	0.2	38.3	0.9	3.6	19.3	30.4
SiO_2	8.5	0.4	38.6	1.5	88.7	21.7	43.9
P_2O_5	nd	0.1	0.2	nd	0.2	nd	nd
K_2O	nd	nd	nd	nd	nd	0.1	nd
CaO	0.3	0.8	nd	0.5	nd	1.2	0.4
TiO_2	0.3	0.1	0.1	0.1	nd	0.2	0.2
V_2O_5	nd	0.1	nd	nd	nd	0.1	nd
MnO	0.1	nd	nd	nd	nd	0.4	0.2
FeO	2.8	0.1	15.5	1.0	2.9	52.8	21.3
CuO	nd	0.3	nd	nd	0.1	0.1	nd
ZnO	nd	nd	0.1	0.1	nd	nd	nd
As_2O_3	nd	0.1	nd	nd	nd	0.9	nd
ZrO_2	nd	nd	nd	nd	nd	0.9	0.2
MoO_3	0.1	nd	0.3	nd	nd	0.5	0.3
SnO_2	75.4	96.3	2.9	94.8	0.2	3.1	0.5
Sb_2O_3	0.4	1.3	nd	1.3	nd	0.4	0.1
WO_3	0.1	0.3	0.3	nd	nd	nd	0.2
Sum	95.6	100.2	102.5	100.7	98.2	102.6	102.0
Scan Mag	x100	x1000	x1000	x1000	x1000	x1000	x1000

The Crift Farm ore is very rich, comprising 75% tin oxide. This is associated with some aluminium, silicon and lesser amounts of iron and sodium. The very small size of the crystals in the Crift Farm ore necessitated that data for individual crystals was obtained using spot analysis. These results indicate that several different types of crystal were present. Spots 1 and 3 are cassiterite, but associated with a small quantity of antimony. The crystals containing sodium, aluminium, silicon and iron are possibly iron-rich biotite mica (Spots 2, 5 and 6), while Spot 4 is most likely quartz with some impurities.

Table 3.17: Chemical composition of Dean Moor Ore Sample 3/28 determined by EDX-SEM (wt%)

Oxide	Bulk	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Na_2O	2.7	0.6	0.7	0.3	5.7	9.8	6.7
MgO	0.9	nd	nd	0.5	nd	0.1	nd
Al_2O_3	6.6	nd	0.2	1.0	17.4	20.1	19.4
SiO_2	14.6	0.5	0.5	1.0	61.9	63.9	59.8
P_2O_5	0.1	nd	nd	nd	nd	nd	nd
K_2O	0.8	nd	nd	nd	8.1	3.0	8.2
CaO	0.8	0.9	0.9	0.7	0.5	0.9	0.7
TiO_2	0.1	0.1	nd	0.1	nd	0.1	nd
V_2O_5	nd	nd	nd	0.1	0.2	nd	nd
MnO	nd	nd	0.1	0.1	0.1	nd	nd
FeO	1.1	1.1	0.8	1.0	0.4	0.2	0.3
CuO	nd	0.1	nd	0.1	0.2	0.1	0.2
ZnO	0.1	0.2	0.1	0.2	nd	nd	0.2
As_2O_3	nd	nd	0.2	nd	nd	nd	nd
ZrO_2	nd	nd	nd	0.1	nd	nd	nd
MoO_3	nd	nd	0.1	0.1	nd	0.1	0.2
SnO_2	67.1	100.8	102.0	98.1	7.1	3.2	6.3
Sb_2O_3	0.4	1.2	0.6	1.1	0.2	nd	nd
WO_3	0.6	0.2	nd	0.2	nd	0.3	nd
Sum	95.7	105.6	106.1	104.7	101.8	101.9	102.1
Scan Mag	x 100	x 1000	x 1000	x 1000	x 1000	x 1000	x 1000

The Dean Moor sample was very small and therefore only a single bulk analysis was carried out, but this shows the sample is rich in tin, comprising 67% of the ore. Silicon and aluminium make up the majority of the remainder of the sample. Iron and Group I oxides are also present.

Two types of mineral grain were clearly visible using this technique. The first type of crystal (Areas 1, 2 and 3) is cassiterite, with traces of impurities such as iron and antimony. The second type of crystal (Areas 4, 5 and 6) contains aluminium and silicon with lesser quantities of sodium and potassium, which is consistent with it being feldspar.

Table 3.18: Chemical composition of Upper Merrivale Ore Sample 4/10 determined by EDX-SEM (wt%)

	Bulk Analyses			Individual crystals		
Oxide	**Area 1**	**Area 2**	**Mean**	**1**	**2**	**3**
Na_2O	1.7	1.7	1.7	0.4	1.5	4.3
MgO	0.5	0.5	0.5	nd	0.2	3.7
Al_2O_3	1.6	0.8	1.2	0.1	nd	27.1
SiO_2	96.5	97.8	97.1	1.4	96.9	36.3
P_2O_5	nd	0.1	0.1	nd	0.4	nd
K_2O	nd	nd	nd	nd	nd	0.1
CaO	0.1	nd	nd	0.8	nd	0.7
TiO_2	nd	nd	nd	0.2	nd	0.2
V_2O_5	0.1	nd	0.1	0.2	nd	nd
MnO	nd	nd	nd	nd	nd	nd
FeO	1.4	0.8	1.1	0.6	nd	28.4
CuO	nd	0.1	0.1	nd	nd	nd
ZnO	nd	nd	nd	nd	nd	nd
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	nd	nd	nd	nd	nd	0.1
MoO_3	nd	nd	nd	nd	nd	0.1
SnO_2	0.5	0.2	0.4	94.3	0.1	0.7
Sb_2O_3	nd	nd	nd	0.6	nd	nd
WO_3	nd	nd	nd	0.7	nd	nd
Sum	102.3	102.0	102.2	99.2	99.1	101.7
Scan Mag	x 50	x 50		x 500	x 500	x 500

The Upper Merrivale sample was scanned at low magnification to obtain its bulk composition, which proved to consist mainly of silica, accompanied by very small amounts of sodium, magnesium, aluminium, iron and tin. This suggests that the majority of the rock fragment is composed of quartz. Tin is an extremely minor constituent.

Spot analysis of individual crystals revealed the presence of cassiterite (Spot 1), quartz (Spot 2) and an alumino-silicate mineral with sodium and magnesium, which could possibly be schorl (Spot 3). The distribution of minerals within the sample is illustrated below (Figure 3.45). The cassiterite took the form of grains approximately 20 μm across

that were finely disseminated throughout the mainly quartz rock. Thin veins of a third mineral, tentatively identified as schorl, ran through the sample.

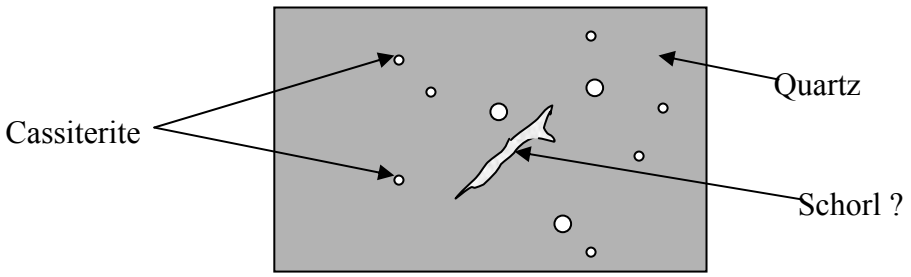


Figure 3.45: Sketch of the distribution of minerals in the Upper Merrivale ore sample.

Table 3.19: Chemical composition of Metherel 'Stream Tin' Sample 4/14 determined by EDX-SEM (wt%)

Oxide	Area 1	Area 2	Area 3	Spot 1
Na_2O	4.1	3.1	3.7	0.1
MgO	4.4	2.7	3.5	nd
Al_2O_3	37.9	24.1	35.6	0.1
SiO_2	37.8	56.7	40.5	0.4
P_2O_5	nd	nd	0.1	nd
K_2O	nd	0.1	0.1	nd
CaO	0.7	0.5	0.6	nd
TiO_2	1.4	1.4	1.1	96.9
V_2O_5	0.1	0.1	0.1	1.3
MnO	0.2	0.1	0.1	nd
FeO	16.3	12.7	15.5	0.4
CuO	nd	0.1	0.1	nd
ZnO	nd	nd	0.1	0.2
As_2O_3	nd	nd	nd	nd
ZrO_2	nd	nd	nd	nd
MoO_3	0.2	nd	0.2	nd
SnO_2	nd	0.1	nd	0.5
Sb_2O_3	nd	nd	nd	nd
WO_3	nd	nd	0.2	0.1
Sum	103.2	101.8	101.5	100.1
Scan Mag	x 100	x 100	x 100	x 1000

Bulk analysis of the Metherel pebble indicates that tin is absent save in trace amounts.

The majority of the sample is composed of the elements silicon, aluminium and iron, with lesser amounts of sodium and magnesium. Spot analysis of some small crystals that were distinguishable only using backscattered electron imaging, showed them to be titania.

Laser Ablation ICPMS

Laser ablation ICPMS was used to obtain semi-quantitative data from the ore (and supposed ore) samples. A mean of the results is provided in Table 3.21 and full data in Appendix 10. It is not possible to compare quantities of different elements between samples, owing to probable differences in the amount of target material ablated, but the relative concentrations of elements within a sample may be compared. A summary of the main findings is given in Table 3.20.

Table 3.20: Summary of ICPMS results for Tin Ores

Sample	Run	Most abundant elements	Other major elements	Minor elements
Caerloggas 4/12	1	Sn	Al W	B Na K Ti Fe Nb Ag Hg
Caerloggas 4/13	1	Sn		Al W
Chysauster 4/30	1	Sn	Si	B Na Mg Al Fe
Crift Farm 4/11	1	Sn	Fe	B Na Al Si K Hg Pb
Crift Farm 4/11	2	Sn	B Na Al Si Fe W Hg	Mg K Mn Cu Zn Pb
Dean Moor 3/48	1	Sn	Na Al Si K Fe	B Mg S
Dean Moor 3/48	2	Sn	Si	B Na Mg Al K Fe
Dean Moor 3/48	3	Sn	Na Al Si K Fe	B Mg P Ca Ti W Hg Pb
Dean Moor 3/48	4	Sn	Na Al Si K Fe	B Mg P Ca Ti W Hg
Upper Merrivale 4/10	1	Si	B Mg Al Fe	Na K Ca Sr Sn Hg
Upper Merrivale 4/10	2	Al Si Fe	B Na Mg Ca	Li K Ti Mn Sr Sn Hg Th
Metherel 4/14	1	Al Si Fe	B Na Mg K	P Ca Ti Mn Sn Hg
Metherel 4/14	2	Al Fe	B Na Mg Si K	Ca Ti Sn Hg

Table 3.21: Mean Results of ICPMS Analysis of Tin Ores

Sample	**7Li** ppm	**9Be** ppm	**11B** ppm	**23Na** ppm	**24Mg** ppm	**27Al** ppm	**29Si** ppm	**31P** ppm	**33S** ppm	**39K** ppm	**44Ca** ppm
Mean of Caerloggas 4/12	37	1	301	562	20	1081	507	4	pnq	136	24
Mean of Caerloggas 4/13	0	1	0	pnq	0	223	pnq	0	pnq	37	pnq
Mean of Chysauster 4/30	3	1	460	151	170	799	3688	32	pnq	47	44
Mean of Crift Farm 4/11	9	1	2509	3431	582	8379	4490	105	pnq	1028	183
Mean of Crift Farm 4/11	4	1	1438	2790	318	5912	3029	57	pnq	902	47
Mean of Dean Moor 3/48	50	30	2650	11220	2823	23750	37290	462	1556	14980	519
Mean of Dean Moor 3/48	45	19	1368	6093	1517	8147	11900	266	15	2200	602
Mean of Dean Moor 3/48	21	14	785	2986	357	3532	6995	164	pnq	1472	489
Mean of Dean Moor 3/48	15	16	473	3214	472	4058	2790	187	pnq	1841	586
Mean of Upper Merrivale 4/10	5	1	486	36	244	744	2325	0	pnq	30	38
Mean of Upper Merrivale 4/10	11	1	587	808	417	1319	2696	0	pnq	42	418
Mean of Metherel 4/14	26	1	5797	4672	3694	21510	10080	159	pnq	1216	336
Mean of Metherel 4/14	18	0	5687	4958	3153	19850	8492	61	pnq	1013	257

pnq = present not quantifiable XXXXX = detector swamped

Sample	45Sc ppm	47Ti ppm	51V ppm	52Cr ppm	55Mn ppm	56Fe ppm	59Co ppm	60Ni ppm	65Cu ppm	66Zn ppm	69Ga ppm	72Ge ppm
Mean of Caerloggas 4/12	47	149	1	0	14	744	0	3	48	20	4	0
Mean of Caerloggas 4/13	0	37	0	0	0	27	0	0	0	1	1	0
Mean of Chysauster 4/30	0	8	0	0	3	946	0	2	1	1	3	0
Mean of Crift Farm 4/11	0	126	4	4	73	10480	6	5	346	432	6	1
Mean of Crift Farm 4/11	0	94	3	4	140	7545	3	3	136	150	4	0
Mean of Dean Moor 3/48	8	622	26	4	27	11850	3	20	19	45	24	2
Mean of Dean Moor 3/48	4	358	22	3	22	5607	1	12	67	97	8	1
Mean of Dean Moor 3/48	4	332	29	4	19	3477	1	8	64	87	4	1
Mean of Dean Moor 3/48	1	243	12	3	21	3334	1	6	35	69	5	0
Mean of Upper Merrivale 4/10	0	4	1	0	8	905	0	0	0	3	1	0
Mean of Upper Merrivale 4/10	0	10	2	0	21	1702	0	1	1	7	2	0
Mean of Metherel 4/14	1	660	15	4	230	14990	3	12	8	44	14	1
Mean of Metherel 4/14	3	911	29	13	99	13010	4	15	17	57	15	0

Sample	75As ppm	82Se ppm	85Rb ppm	88Sr ppm	89Y ppm	90Zr ppm	93Nb ppm	95Mo ppm	101Ru ppm	103Rh ppm	105Pd ppm	107Ag ppm
Mean of Caerloggas 4/12	3	0	2	2	0	60	162	0	0	0	0	561
Mean of Caerloggas 4/13	1	0	0	0	0	2	4	0	0	0	0	0
Mean of Chysauster 4/30	0	0	0	6	0	0	3	0	0	0	0	0
Mean of Crift Farm 4/11	120	0	4	17	5	8	43	1	0	0	0	31
Mean of Crift Farm 4/11	94	0	4	12	2	5	22	3	0	0	0	14
Mean of Dean Moor 3/48	56	0	48	27	5	297	31	0	0	0	0	10
Mean of Dean Moor 3/48	12	0	11	20	1	29	15	0	0	0	0	15
Mean of Dean Moor 3/48	8	0	6	10	1	23	29	0	0	0	0	26
Mean of Dean Moor 3/48	5	0	8	6	0	23	13	0	0	0	0	5
Mean of Upper Merrivale 4/10	0	0	0	16	1	0	0	0	0	0	0	0
Mean of Upper Merrivale 4/10	1	0	0	33	5	0	0	0	0	0	0	0
Mean of Metherel 4/14	3	0	12	27	2	6	2	0	0	0	0	1
Mean of Metherel 4/14	0	0	5	16	1	23	2	0	0	0	0	1

Sample	111Cd ppm	118Sn ppm	121Sb ppm	125Te ppm	133Cs ppm	137Ba ppm	139La ppm	140Ce ppm	141Pr ppm	146Nd ppm	147Sm ppm	153Eu ppm
Mean of Caerloggas 4/12	1	226400	2	1	2	8	0	1	0	0	0	0
Mean of Caerloggas 4/13	0	22150	0	0	0	1	0	0	0	0	0	0
Mean of Chysauster 4/30	0	12690	1	0	0	1	0	1	0	0	0	0
Mean of Crift Farm 4/11	1	176300	7	2	1	71	3	5	1	3	1	0
Mean of Crift Farm 4/11	0	104300	5	0	1	61	3	4	2	8	2	0
Mean of Dean Moor 3/48	1	XXXXX	80	1	11	24	5	9	1	7	1	0
Mean of Dean Moor 3/48	1	XXXXX	83	1	3	15	2	2	0	1	0	0
Mean of Dean Moor 3/48	1	390900	88	1	2	21	1	2	0	1	0	0
Mean of Dean Moor 3/48	1	400900	66	1	3	20	1	2	0	1	0	0
Mean of Upper Merrivale 4/10	0	30	0	0	0	0	0	1	0	1	1	0
Mean of Upper Merrivale 4/10	0	63	0	0	1	0	2	6	2	9	5	1
Mean of Metherel 4/14	0	233	1	0	6	20	4	7	1	3	1	0
Mean of Metherel 4/14	0	245	1	0	2	14	3	6	1	3	1	0

Sample	157Gd ppm	159Tb ppm	163Dy ppm	165Ho ppm	166Er ppm	169Tm ppm	172Yb ppm	175Lu ppm	178Hf ppm	181Ta ppm	182W ppm	185Re ppm
Mean of Caerloggas 4/12	0	0	0	0	0	0	0	0	7	33	1100	0
Mean of Caerloggas 4/13	0	0	0	0	0	0	0	0	2	18	488	0
Mean of Chysauster 4/30	0	0	0	0	0	0	0	0	0	2	84	0
Mean of Crift Farm 4/11	1	0	1	0	1	0	1	0	0	2	507	0
Mean of Crift Farm 4/11	2	0	1	0	0	0	1	0	0	2	8748	0
Mean of Dean Moor 3/48	1	0	1	0	1	0	2	0	8	9	397	0
Mean of Dean Moor 3/48	0	0	0	0	0	0	0	0	2	6	270	0
Mean of Dean Moor 3/48	0	0	0	0	0	0	0	0	2	15	470	0
Mean of Dean Moor 3/48	0	0	0	0	0	0	0	0	2	7	396	0
Mean of Upper Merrivale 4/10	1	0	1	0	0	0	1	0	0	0	0	0
Mean of Upper Merrivale 4/10	5	1	5	1	2	0	3	0	0	0	0	0
Mean of Metherel 4/14	1	0	1	0	0	0	0	0	0	1	7	0
Mean of Metherel 4/14	0	0	0	0	0	0	1	0	1	0	8	0

Sample	189Os ppm	193Ir ppm	195Pt ppm	197Au ppm	202Hg ppm	205Tl ppm	208Pb ppm	209Bi ppm	232Th ppm	238U ppm
Mean of Caerloggas 4/12	0	0	0	0	235	0	47	2	0	2
Mean of Caerloggas 4/13	0	0	0	0	25	0	10	2	0	2
Mean of Chysauster 4/30	0	0	0	0	48	0	6	0	0	1
Mean of Crift Farm 4/11	0	0	0	4	3130	0	2025	149	2	16
Mean of Crift Farm 4/11	0	0	0	3	2581	0	599	64	5	16
Mean of Dean Moor 3/48	0	0	0	0	167	0	43	3	4	41
Mean of Dean Moor 3/48	0	0	0	0	180	0	53	1	2	50
Mean of Dean Moor 3/48	0	0	0	1	144	0	127	3	2	69
Mean of Dean Moor 3/48	0	0	0	1	158	0	88	1	2	59
Mean of Upper Merrivale 4/10	0	0	0	0	28	0	0	0	3	1
Mean of Upper Merrivale 4/10	0	0	0	0	46	0	1	0	10	2
Mean of Metherel 4/14	0	0	0	0	160	0	73	1	11	7
Mean of Metherel 4/14	0	0	0	1	170	0	46	1	5	3

The abundance of tin in the samples from Caerloggas, Chysauster, Crift Farm and Dean Moor is confirmed. That it is so much less abundant in the ore from the dump at Upper Merrivale suggests that this ore was reject material. The amount of tin present in the Metherel sample is lower still.

Antimony is apparently absent in the Crift Farm sample, as analysed by ICPMS. This may indicate an irregular distribution of this element within the ore. The presence of boron in the ore from Upper Merrivale supports the identification of Crystal 3 as schorl.

X-ray Diffraction:

X-ray spectra for the samples from Caerloggas, Chysauster, Crift Farm, Upper Merrivale and Metherel are shown in Figures 3.46 to 3.53. Ideal spectra for the minerals stated are superimposed on the spectra of the ores to aid comparison. A summary of the major minerals identified using XRD is shown in Table 3.22.

Table 3.22: Summary of Major Minerals in Tin Ores identified using XRD

Sample	Major minerals
Caerloggas 4/12	Cassiterite, Quartz
Caerloggas 4/13	Cassiterite, Quartz
Chysauster 4/30	Cassiterite
Crift Farm 4/11	Cassiterite
Upper Merrivale 4/10	Quartz
Metherel 4/14	Schorl

The presence of cassiterite is confirmed for both Caerloggas samples, and those from Crift Farm and Chysauster. There is insufficient cassiterite in the Upper Merrivale sample for it to be positively identifiable by this method. The Metherel pebble is identified as schorl.

Figure 3.46: XRD Spectrum of Caerloggas ore (Cassiterite)

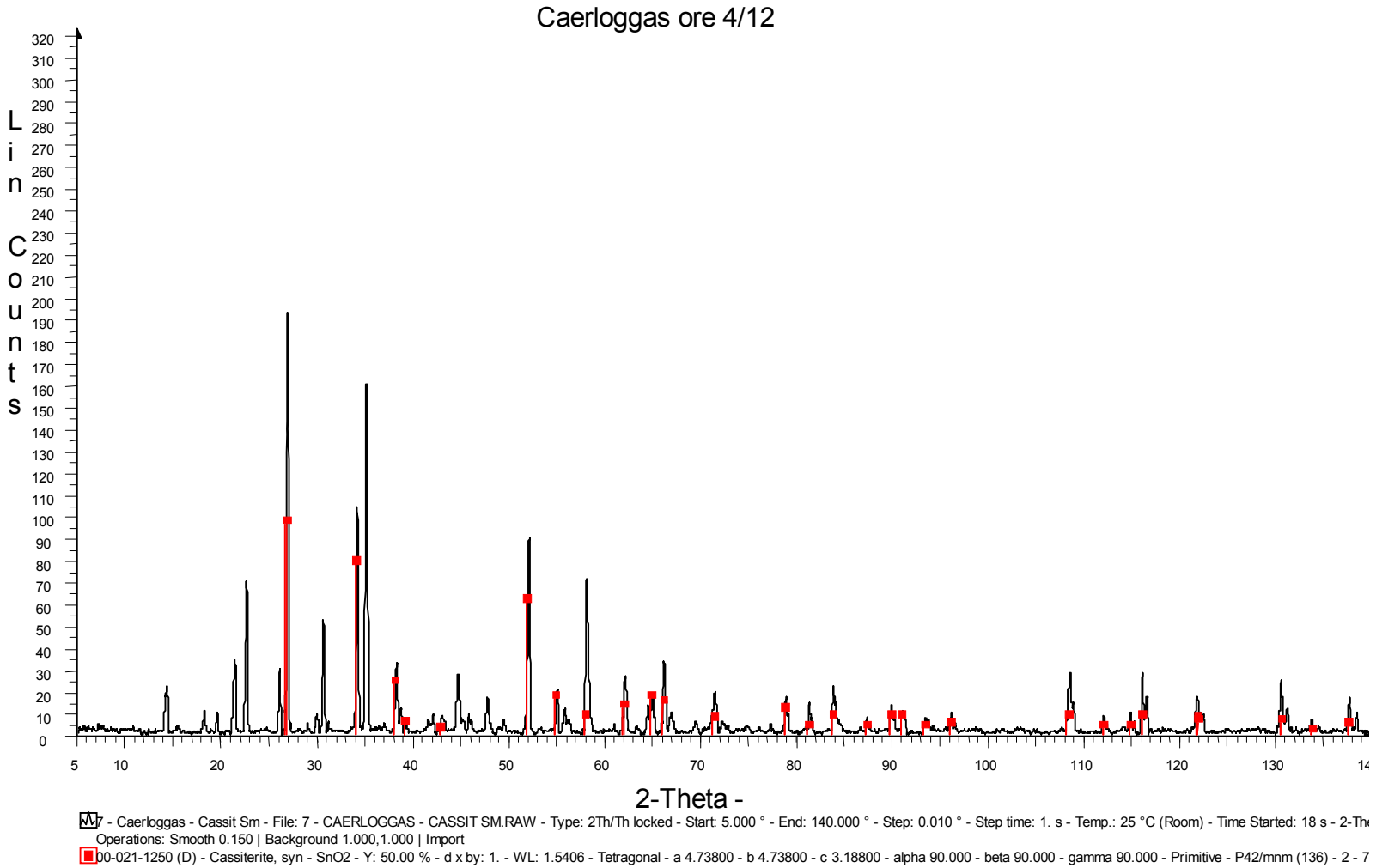


Figure 3.47: XRD Spectrum of Caerloggas ore (Quartz)

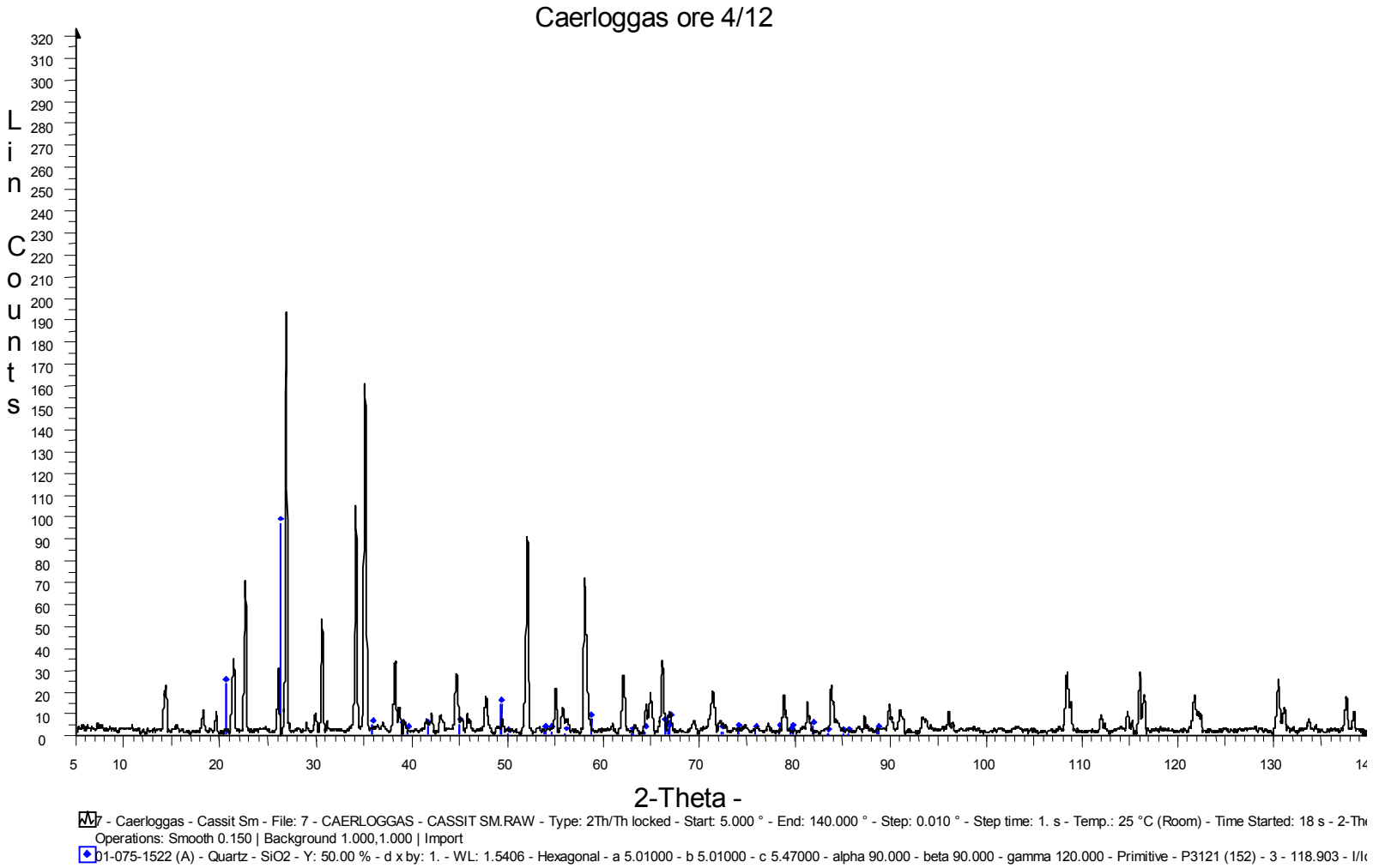


Figure 3.48: XRD Spectrum of Caerloggas ore (Cassiterite)

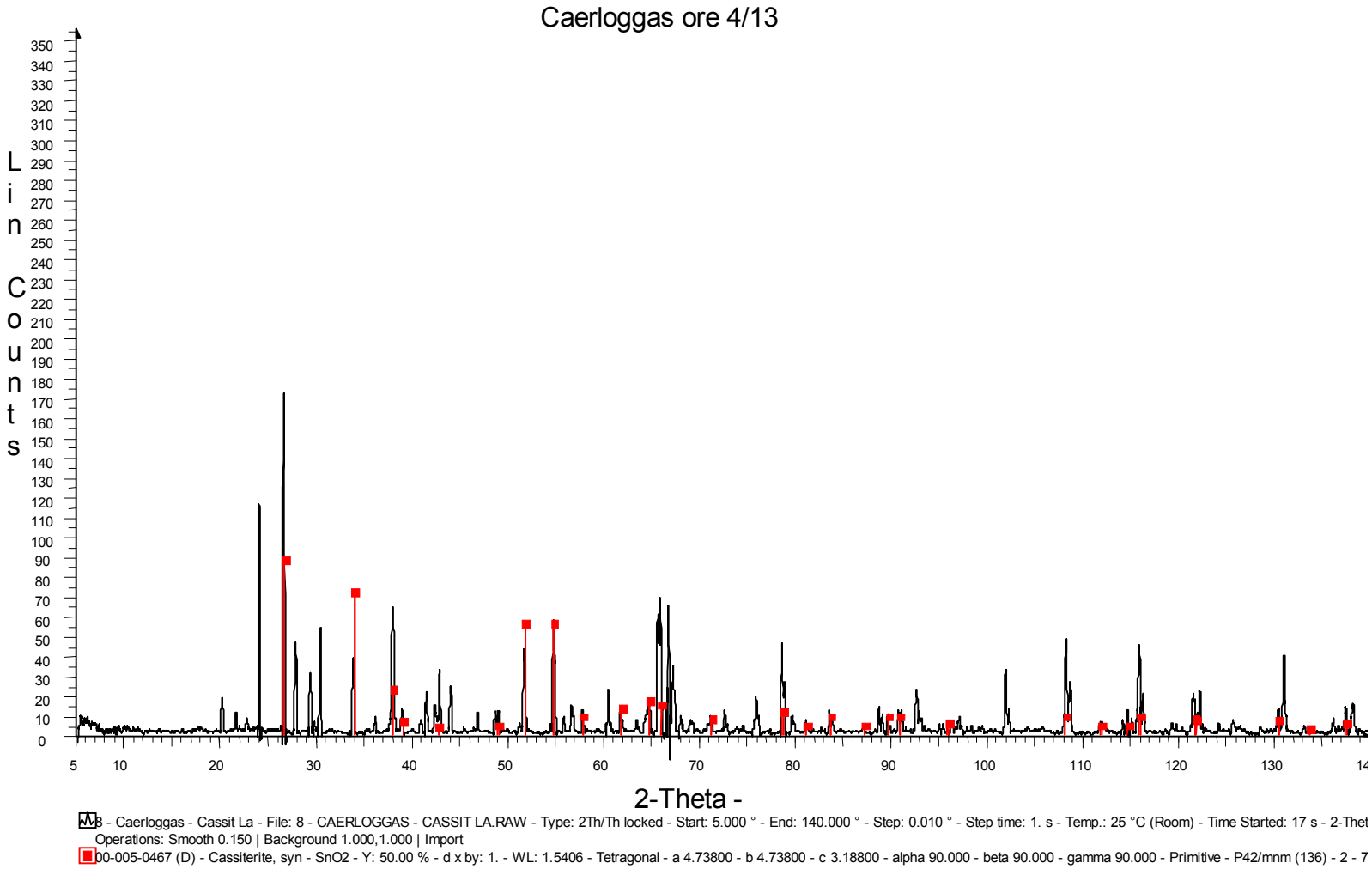


Figure 3.49: XRD Spectrum of Caerloggas ore (Quartz)

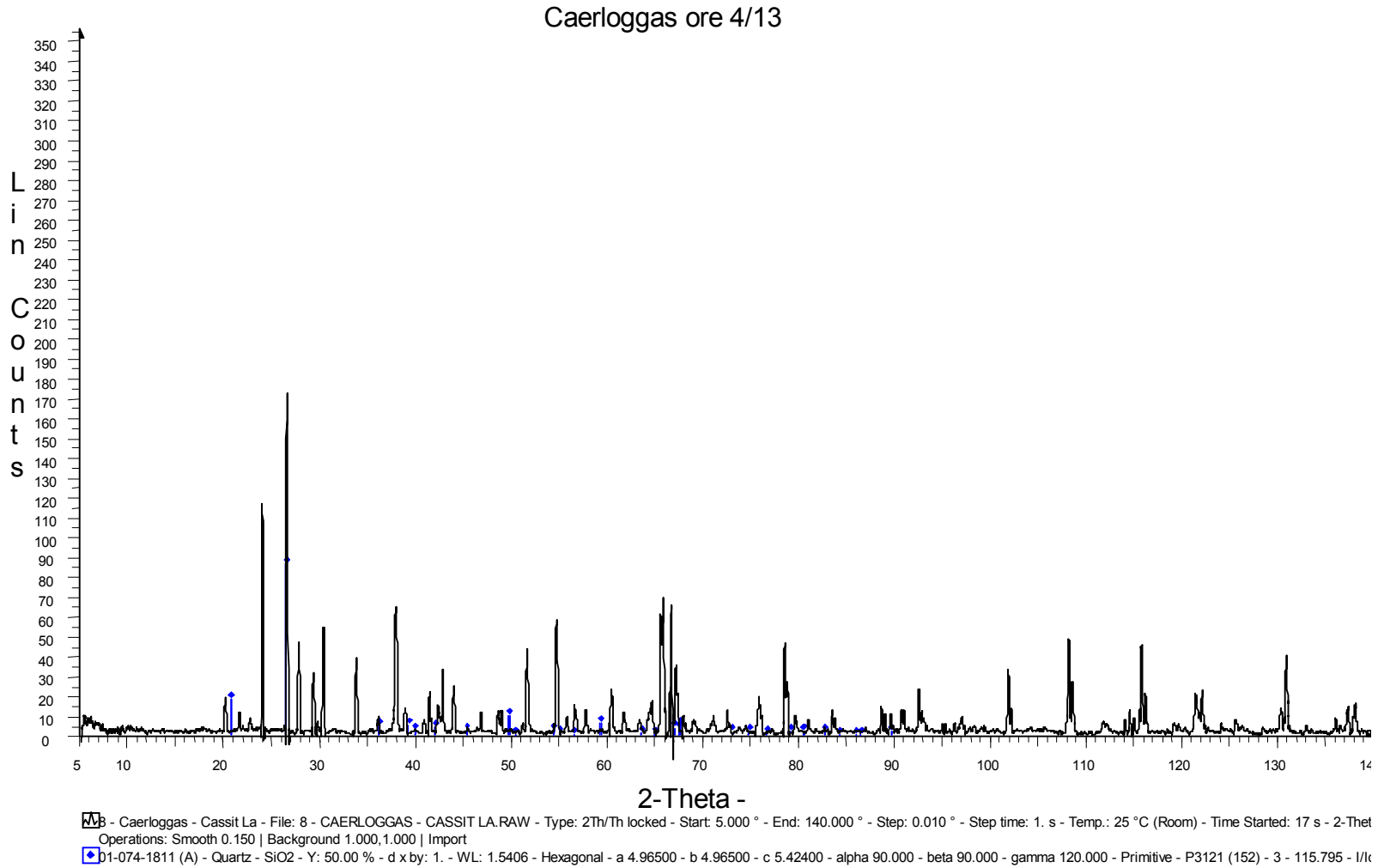


Figure 3.50: XRD Spectrum of Chysauster ore (Cassiterite)

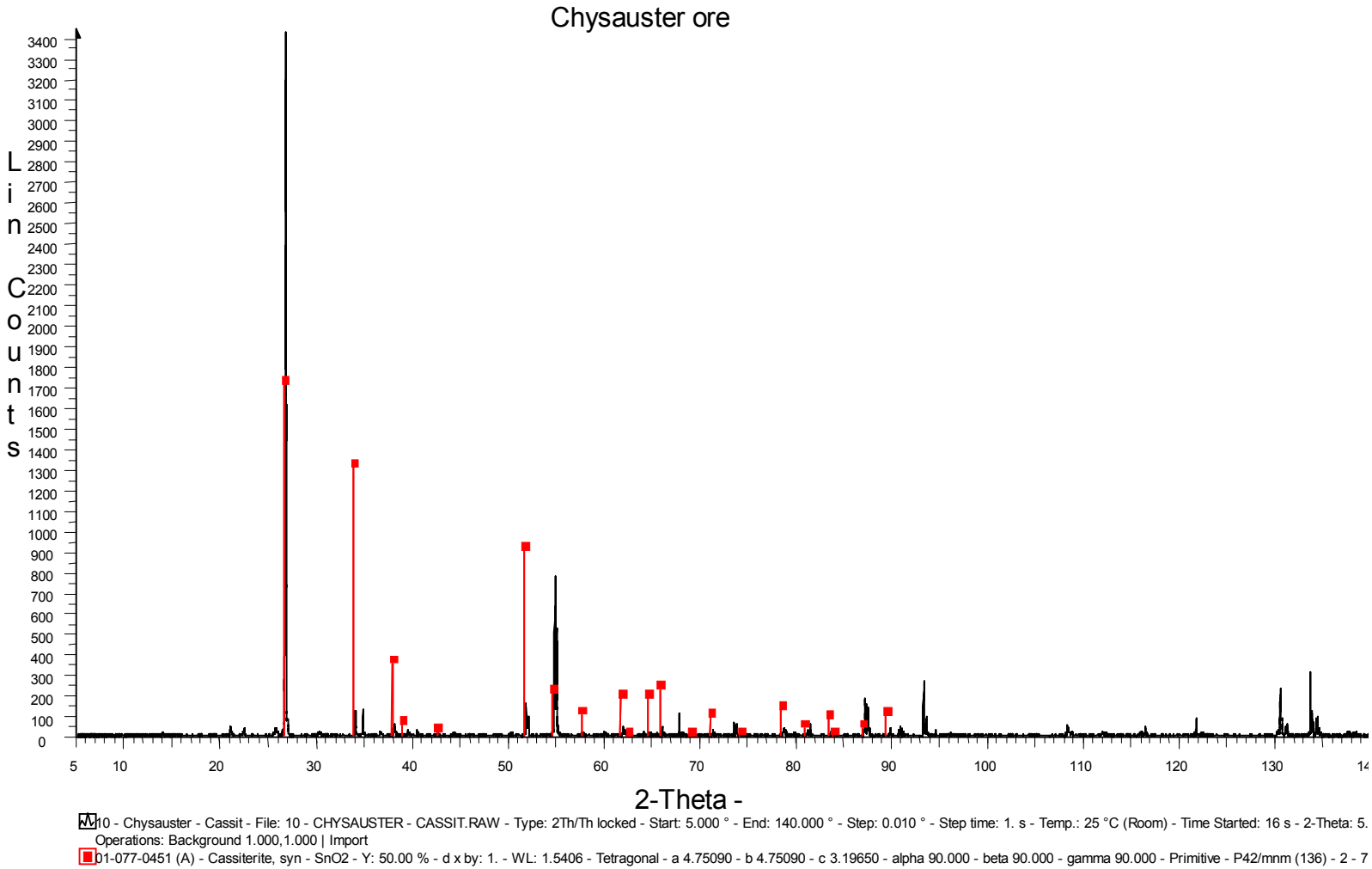


Figure 3.51: XRD Spectrum of Crift Farm ore (Cassiterite)

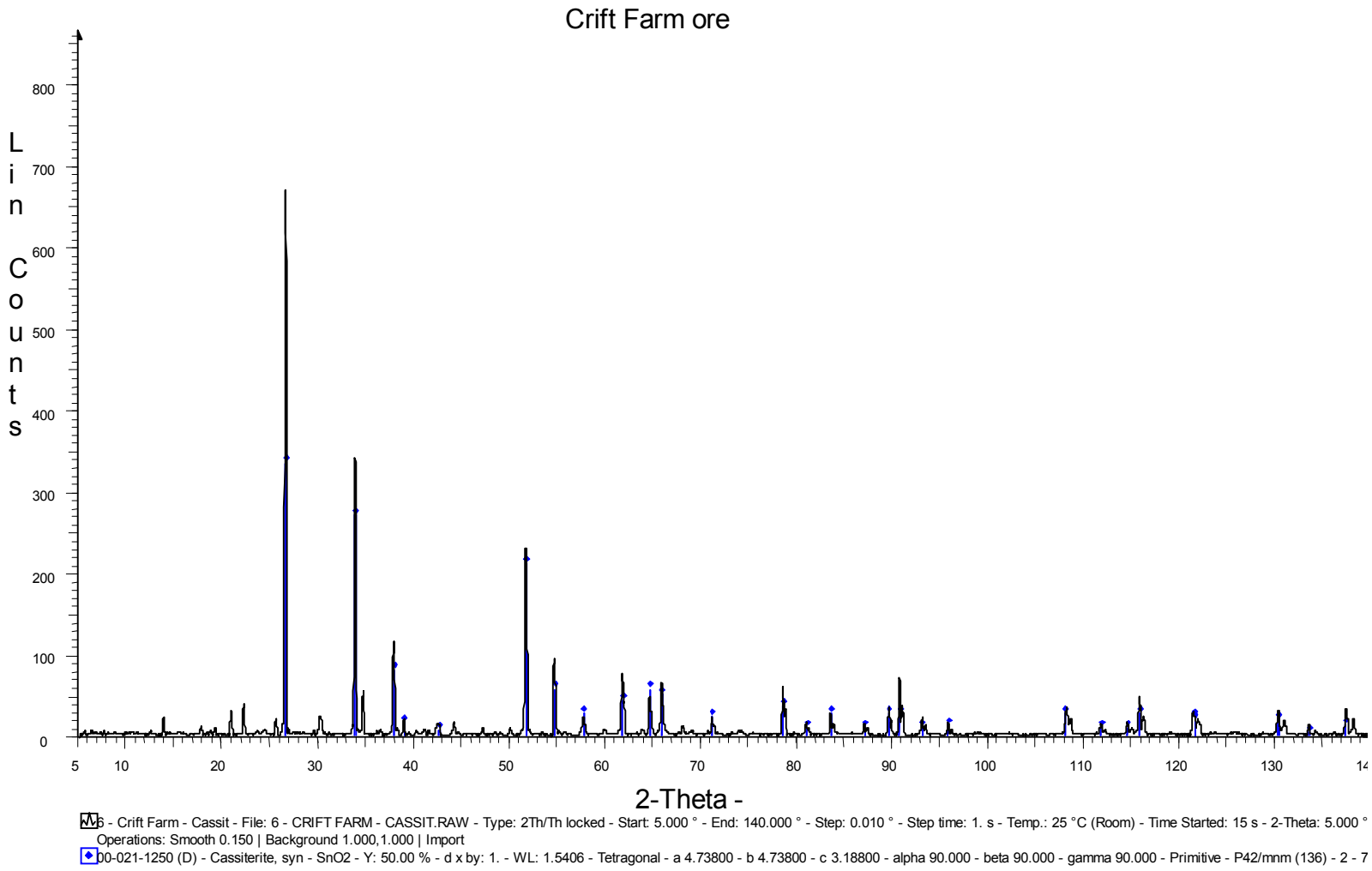


Figure 3.52: XRD Spectrum of Upper Merrivale ore (Quartz)

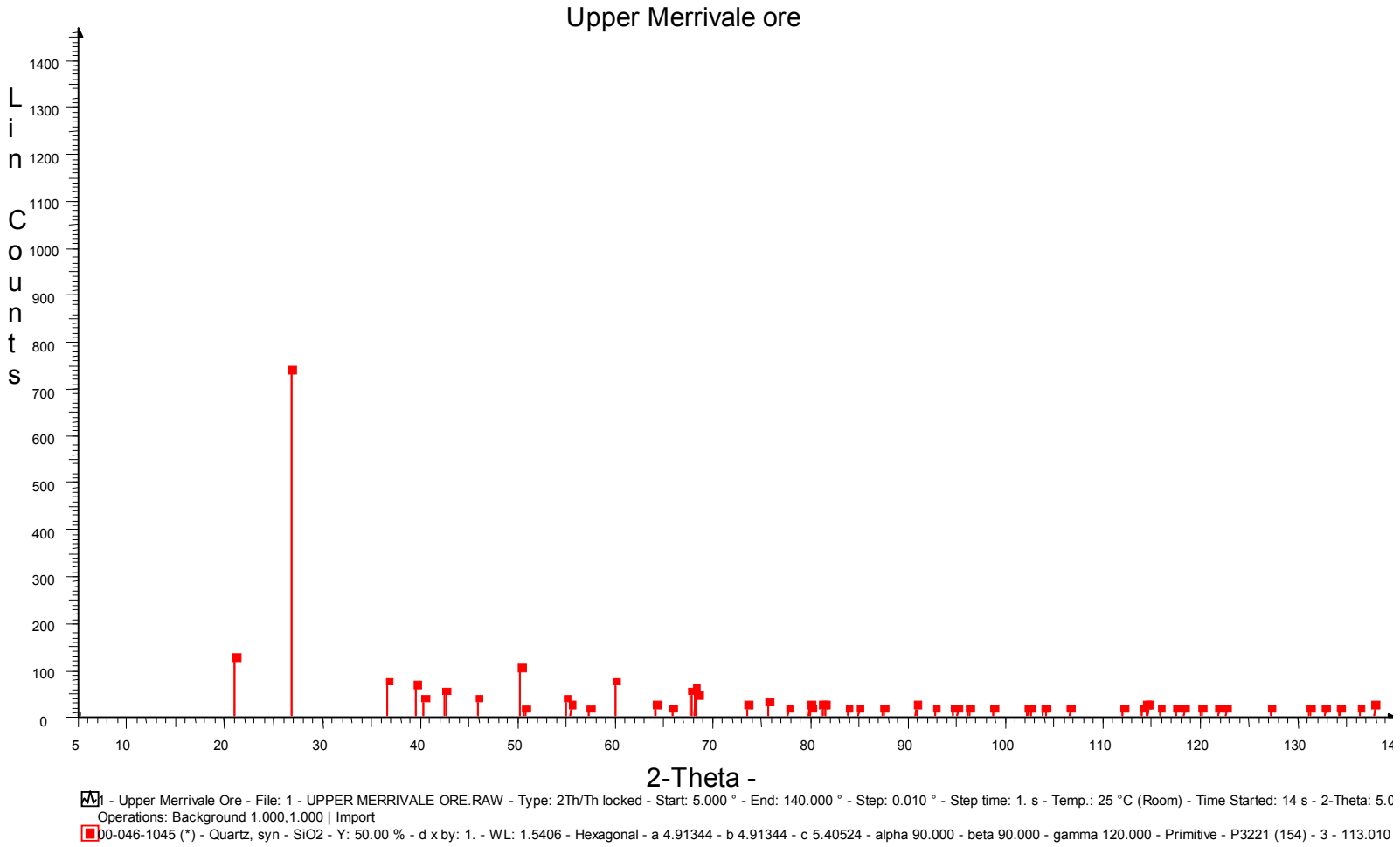
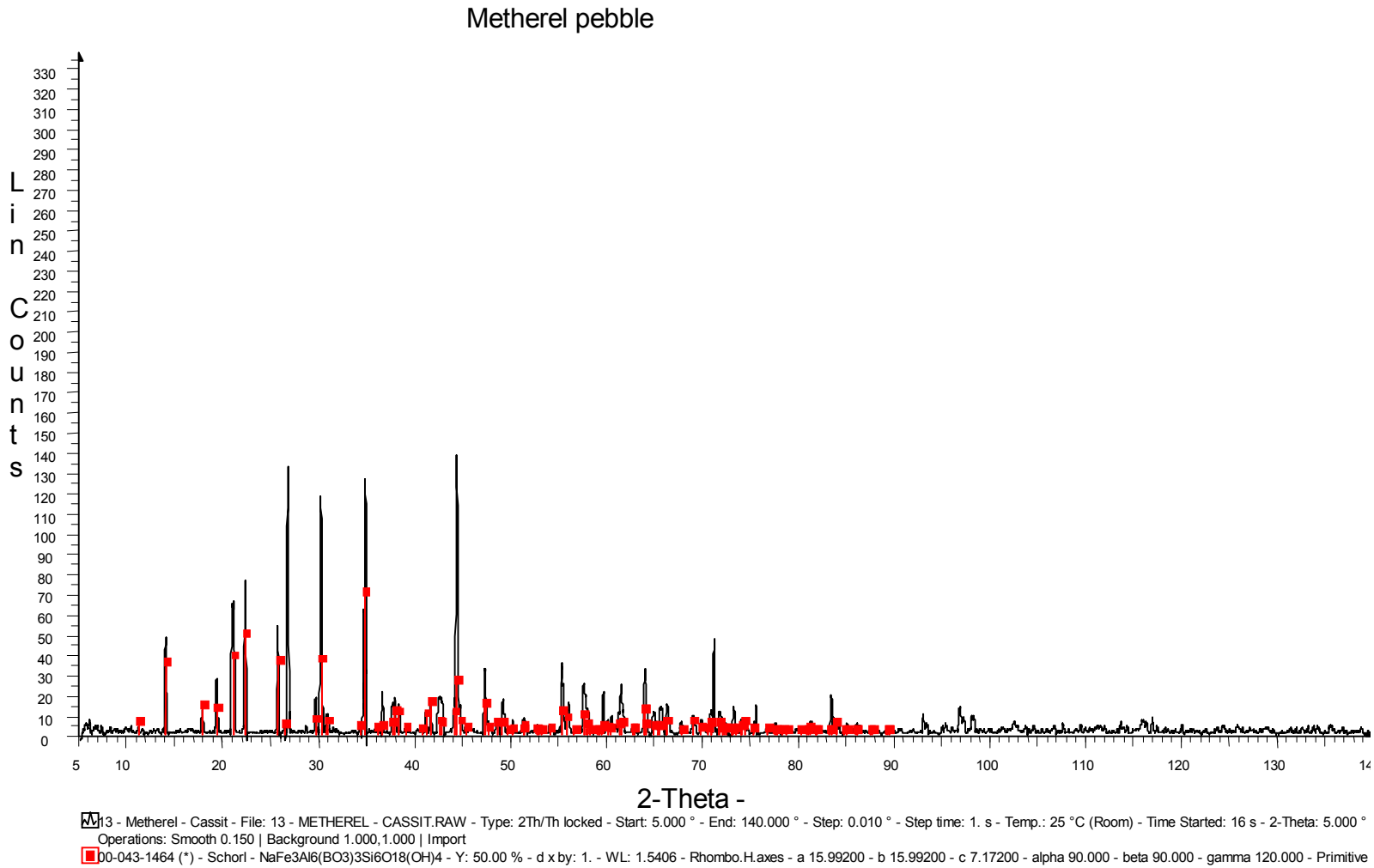


Figure 3.53: XRD Spectrum of Metherel pebble (Schorl)



3.2.3: Summary of Ore Analysis

Cassiterite is a difficult mineral to recognize in hand specimen and it transpires that the black shiny mineral from Metherel has been misidentified: it is schorl not cassiterite.

The other samples, however, have been confirmed as cassiterite-bearing ores (though very poor ones in the case of Upper Merrivale).

The samples from the prehistoric sites were extremely rich in cassiterite. The rocks themselves were relatively soft: easily crushable using minimal force. Separation of the cassiterite from the gangue minerals could have been accomplished with rudimentary crushing and washing.

When it was examined in the 1950s, the accessory minerals in the Dean Moor specimen were identified as quartz and decomposed feldspar, and the results of this new analysis are consistent with the latter being present. The reddish colour of the Dean Moor sample was attributed to the presence of ferric iron in addition to cassiterite. ICPMS analysis indicates that iron is a constituent of this ore. Some iron may be bound up in the crystal structure of the gangue minerals, but SEM spot analysis of individual crystals suggests that at least some may be present as a replacement ion in cassiterite.

The samples from later sites, which were almost certainly vein ores to judge by their appearance, were very hard and could be crushed only with difficulty. The Crift Farm ore was shown to hold abundant cassiterite, comparable to the prehistoric stream tin samples, though it too was associated with some quartz and other less easily identifiable gangue minerals.

The fragments of rock in the ‘ore dump’ at Upper Merrivale do contain cassiterite. This is present in the form of small isolated crystals within a matrix of quartz. Schorl also appears to be present within the rock. In comparison to the stream tin pebbles, this material is very poor. The tinners operating the stamps would recognize this fact (either from the appearance of the rock or by the specific gravity of the fragments, which would be noticeably greater if tin was present in any great quantity), which explains why it was left on the dump.

Although the amount of information obtained from analysis of ores is small, these observations may be related to the data from the slags in a general way. The size and types of gangue minerals in the ore specimens and the manner in which the ore was processed will directly influence the appearance of the slag, so it is useful to know what ores were being selected (and rejected) by smelters at different periods. The results are discussed in Section 4.2.

3.3: Results of Furnace Wall Material Analysis

3.3.1: Physical Characteristics of Furnace Wall Material

A description of furnace wall materials/furnace linings is given in Table 3.23, and photographs of some of these samples are presented in the Image Gallery, File 5 (see CD-ROM).

Table 3.23: Description of Furnace Wall Materials

Site	Dimensions (cm)	Description
Avon Dam	4 x 3 x 2	A small irregular shaped block with a layer of black slag 1-2mm thick adhering to one surface. Beneath the slag layer is a 2cm thick layer composed of light and dark flecks, which may be vitrified granite. This adheres to an uneven 2cm thick layer of what appears to be reddish clay.
Eggworthy (Left Bank)	2 x 3 x 3	Irregular block of granite from outside the mill structure on the left bank of the river. A layer of black slag approx. 5mm thick adheres to one surface. The granite is vitrified and pale pink in colour.
Eylesbarrow	9 x 9 x 7	A smooth layer of reddish brown slag approx. 1mm thick overlies a c.1cm thick layer of material consisting of single large white crystals. The crystalline layer adheres to, but appears not to have blended into, a sub-rectangular piece of brick. The colour of the brick changes from brown to cream then orangey-pink with distance from the slagged surface.
Eylesbarrow	4 x 5 x 3 and 3 x 2 x 2	Two small irregular fragments of what appears to be vitrified granite: the material consists of mm-scale clear, white and black crystals. Both samples have a thin coating of maroon slag over one surface.
Godolphin	8 x 6 x 6	The original slab appeared to be weathered clay, with one surface coated with a thin c.1mm layer of a reddish maroon material, possibly slag or burnt clay. Freshly exposed surfaces revealed pale cream-coloured dried and cracked clay, which contained substantial mineral (quartz?) fragments. All parts of the sample were nonmagnetic. The slab measured 8 x 6cm across the slagged surface, and was 6cm thick. Approximately one third of the slab was made available for analysis.

Upper Merrivale Context 58 Sample UMF01	7 x 5 x 2.5	A small fragment of granite with slag adhering to one face. On the surface the slag is matt and greyish brown, but its edges reveal it to be glassy and black. There are indications of small bubbles approx. 1mm in diameter in the slag. The slag layer overlies a layer of vitrified material approx. 3cm thick, visible on the sides of the sample, consisting of mm-scale clear, white and black crystals. This in turn grades into a layer composed of pinkish fine-grained granite, containing clear, pink and black crystals.
Upper Merrivale Context 522 Sample UMF02	4 x 8 x 5	Irregular-shaped piece of granite with slag covering one face, which is flat. The slag appears matt, mostly brown in colour, with occasional areas of black. Thicker trails of slag containing burst bubbles 1-2mm across are visible on this surface: these lines may be drips or may be the result of slag lapping against the furnace wall. Beneath the slag layer the sample has been vitrified to a depth of 3cm on one side and 0.5cm on the other. This layer is pale grey/white, flecked with black. The vitrified layer then grades into unaffected granite. It is a dark pinkish-brown, containing clear, pink and black crystals. It is fine-grained overall, but contains some larger crystals.
Upper Merrivale Context 1512 Sample UMF03	7 x 7 x 3	A sub-rectangular piece of granite with slag adhering to one flat face. The surface of the slag is matt and greyish brown. It contains the remains of burst bubbles measuring 1-5mm across. The edges of the 1mm thick slag layer are black and glassy, indicating that the surface colouration is the result of weathering. The slag layer overlies a vitrified layer approx. 1.5cm thick. It is grey/white and contains clear crystals and a few flecks of a dark mineral. This layer grades into pale pink granite, which is extremely friable. It is composed of very fine clear, pink and black mineral grains surrounding larger clear crystals (possibly quartz) approx. 2mm in length.
Upper Merrivale Context 502 Sample UMF04	12 x 11 x 4	An irregular piece of granite with slag adhering to one face, which is flat. Thicker lines in the slag may be drips of molten slag that have flowed down this face or may indicate the level of slag in the furnace. The remains of burst bubbles 1-2mm across occur where the slag is thickest. The surface of the slag is matt, mostly brown, but with occasional areas of black. Directly beneath the approx.1mm thick slag layer the sample is vitrified. It is pale grey/white with flecks of a dark mineral. This layer extends to a depth of 1cm on one side, 2 cm on the other before blending into a layer of dark pinkish-brown granite. This is fine-grained, with clear, pink and black mineral crystals.

Upper Merrivale Context 185	9 x 6 x 6	An approx.1mm thick layer of black slag, weathered to dark brown in places, adheres to a 4cm thick layer of pale grey/white vitrified material, which has in it flecks of a dark mineral. This vitrified layer blends into a 2-3cm thick layer of fine-grained dark pinkish brown granite.
Upper Merrivale Surface Find	20 x 11 x 23	A layer of black slag, weathered to dark brown in places, coats one surface of an irregular block of what appears to be medium grain reddish sandstone. The slag appears to have penetrated into the rock to a depth of about 3cm, giving it a darker colour and a speckled appearance. The parts of the block affected by slag show a more angular fracture than the remainder of the block, the edges of which are more rounded.
South Hill I	9 x 5 x 6	A layer of black glassy slag, weathered to dark brown where it has been exposed, coats one surface of an irregular fragment of granite. The clear and white crystals of the rock are interspersed with black crystals. This reverse face of the sample contains fewer crystals of the black mineral, and is somewhat friable, with some loose crystals.
Stannon Brook	12 x 12 x 5	A c.1mm thick layer of black glassy slag, weathered to dark brown on the surface, adheres to one face of an irregular fragment of granite. The layer beneath appears to be composed of partially melted white mm-scale crystals. This vitrified material blends, over a distance of c.1cm, into a pinkish granite layer that is less obviously heat altered.
Taw River	1 x 2 x 2	A thin layer of slag adheres to a fragment of pale-coloured vitrified granite.
Thornworthy	6 x 3 x 3	A layer of black slag coats one surface of a fragment of vitrified granite, containing clear, white and black crystals.
Week Ford	12 x 8 x 6	A layer of slag 2-10mm thick blends into a pale coloured, coarse-grained material, possibly clay or quartz fragments, which appears to adhere to a thin layer of pale vitrified granite, which in turn blends into reddish fine-grained granite.

The majority of the samples take the form of irregular pieces of granite, ranging in size from a few centimetres across to fist-sized chunks, as shown in Figure 3.54. They are slagged on one face, and reddened and/or made friable by heat on the opposite face, with the centre portion being vitrified. It is probable that these pieces have been

detached from a more substantial block, perhaps chipped off during restoration of the furnace.

Although granite appears to be the material of choice for furnaces, a single surface find from Upper Merrivale suggests that sandstone may also have been used.

Figure 3.54: Furnace Wall Material fragment from Upper Merrivale Context 185 (side view)

One sample - that from Week Ford - appears to have between the granite block and the slagged layer a layer of what may either be dried clay or quartz crystals from heat damaged granite. The sample from Avon Dam is more obviously composed of some refractory material with slag adhering to it. (Other similar examples have been reported from this site (Robert Smerdon pers comm. 30/1/05)). No samples from these sites have been made available for analysis.

One sample from the later-dated furnace at Eylesbarrow was firebrick rather than granite. A thin layer of slag coats one face, but there is no clear vitrified layer beneath the slag coating.

The sample from Godolphin is different from the other samples, having what appears to be a layer of maroon-coloured slag over a cream-coloured clay-like material.

3.3.2: SEM Imaging and X-ray Mapping of Furnace Wall Materials / Furnace Linings

Normal beam imaging with a scanning electron microscope of polished sections of four pieces of the Upper Merrivale furnace wall material showed that at high magnification the microstructure of the adhering slag layer was multi-phased, and often dendritic in nature (see Figure 3.55).

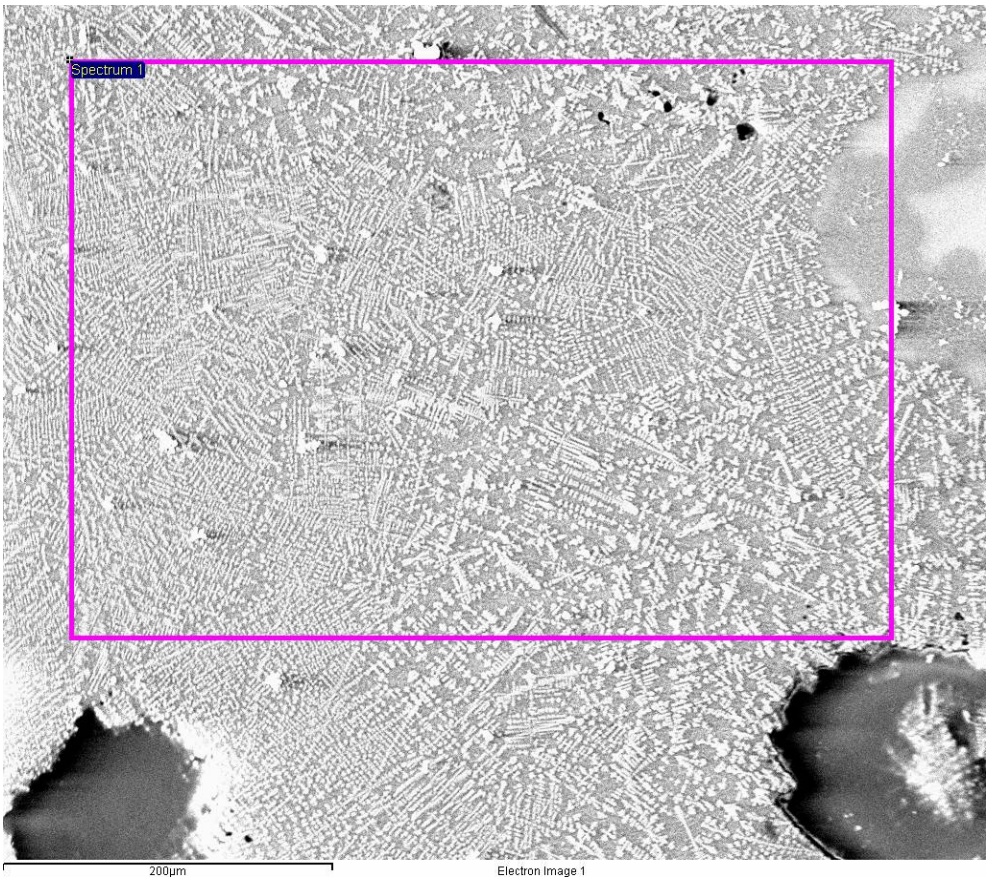


Figure 3.55: SEM image showing the microstructure of the thin slag layer in sample UMF01. The dark tin-rich slag matrix contains paler iron and titanium rich dendrites

X-ray mapping showed that the layer of slag on the surface of the block is very thin: 2mm at most, and usually less than 1mm. The boundary between the slag and the crystals in the granite appears to be sharp (see Figure 3.56a).

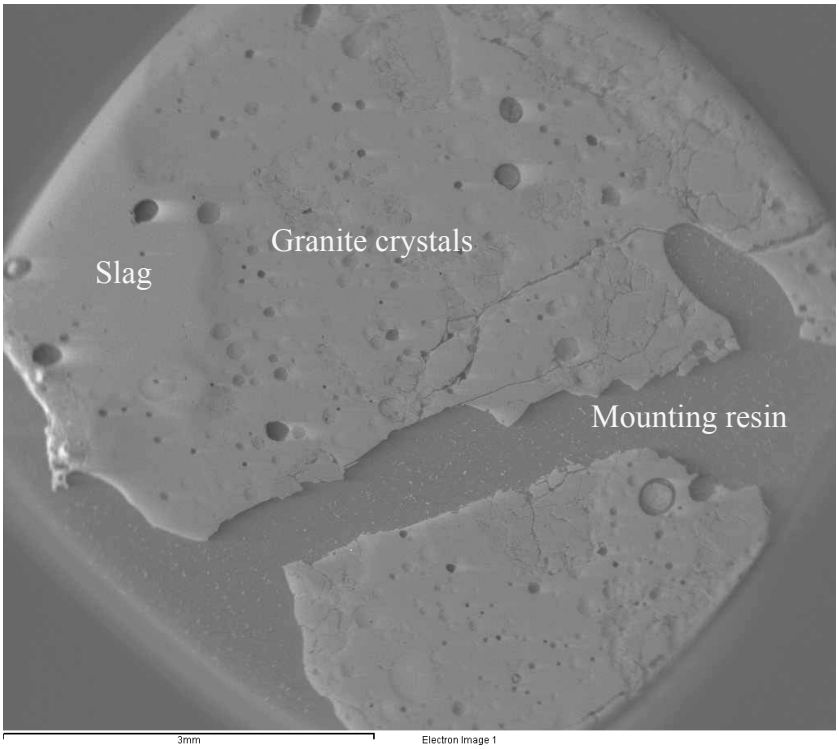


Figure 3.56a: SEM image showing the boundary between the slag layer and the granite of sample UMF01, which is composed of 3 different mineral crystals.

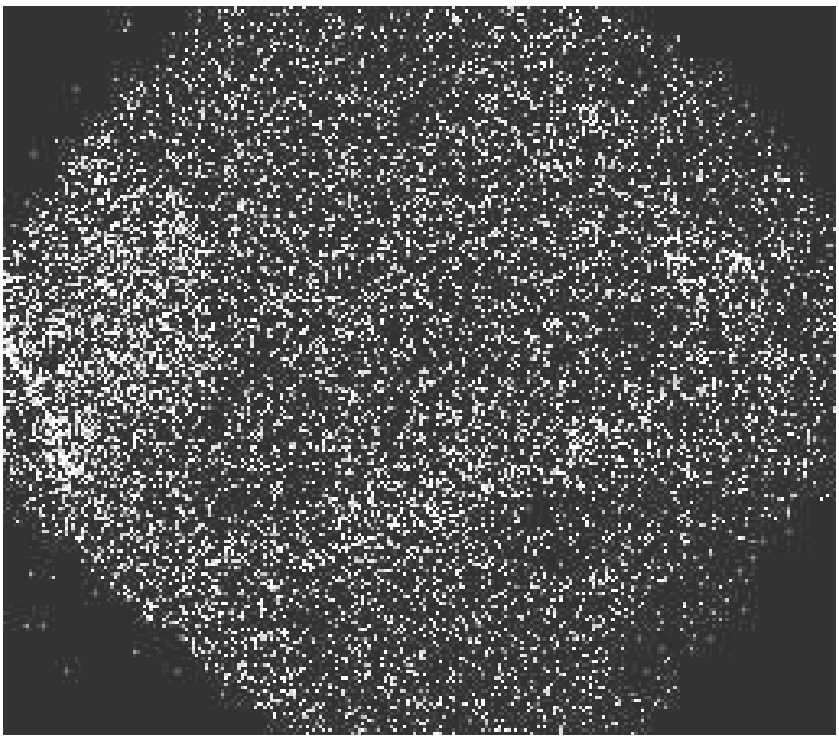


Figure 3.56b: X-ray map showing distribution of calcium (Ca Kα1) in sample UMF01

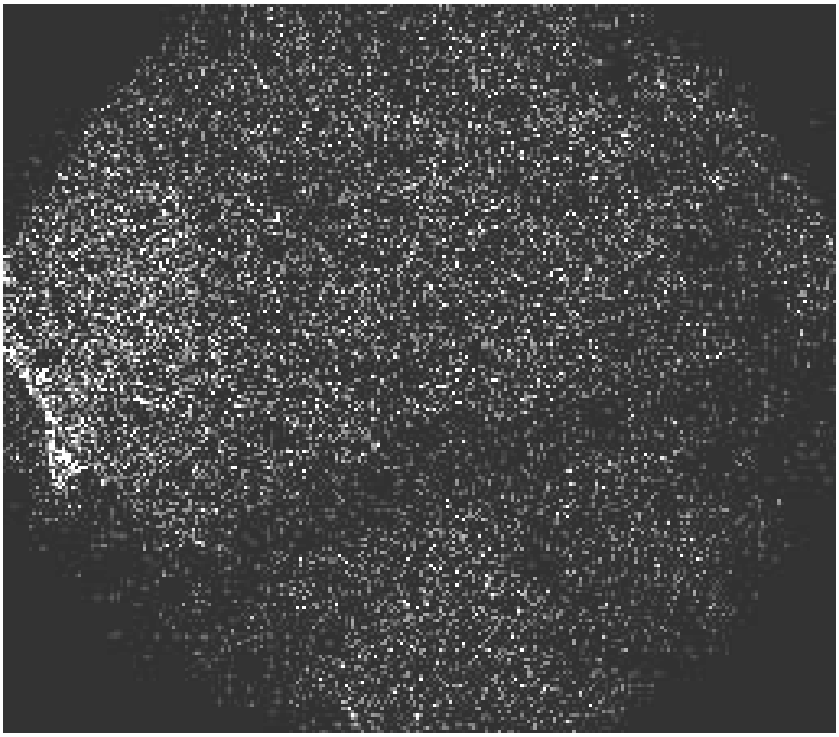


Figure 3.56c: X-ray map showing distribution of tin (Sn Lα1) in sample UMF01

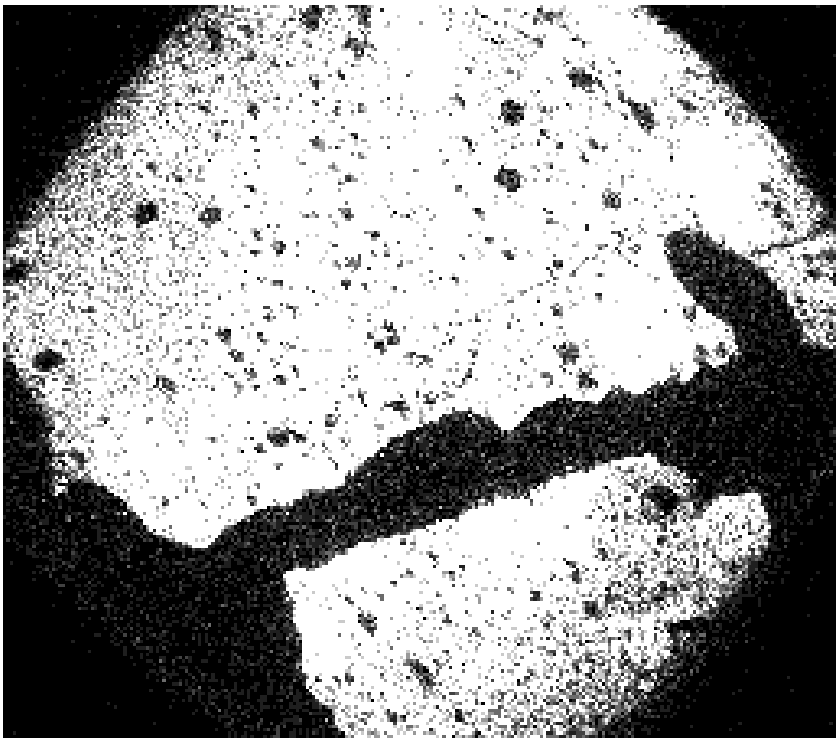


Figure 3.56d: X-ray map showing distribution of silicon (Si Kα1) in sample UMF01

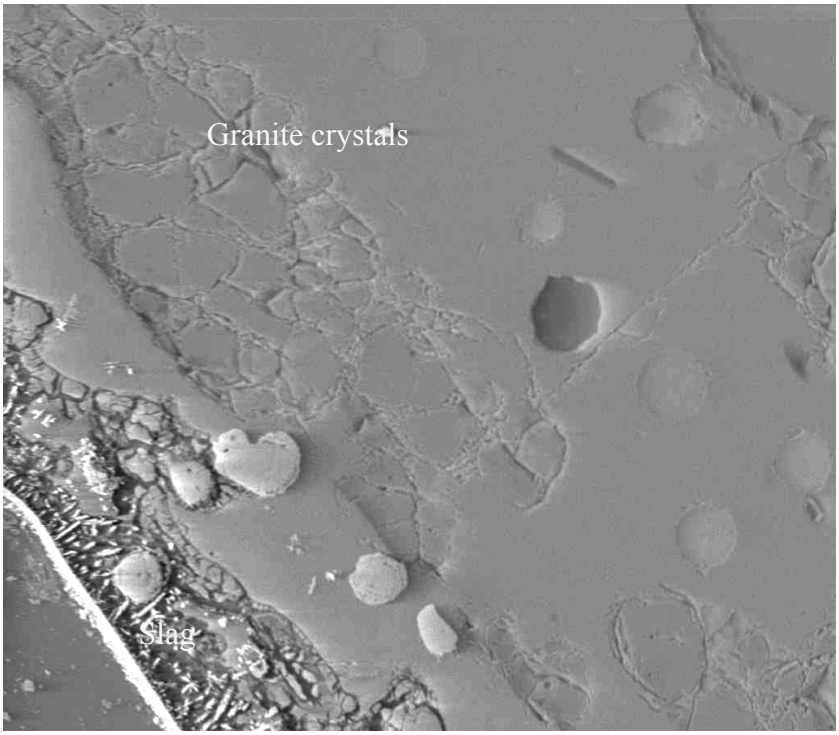


Figure 3.57a: SEM image of sample UMF02, showing the mineral crystals making up the granite and a thin line of phased slag running diagonally across the bottom left of the image

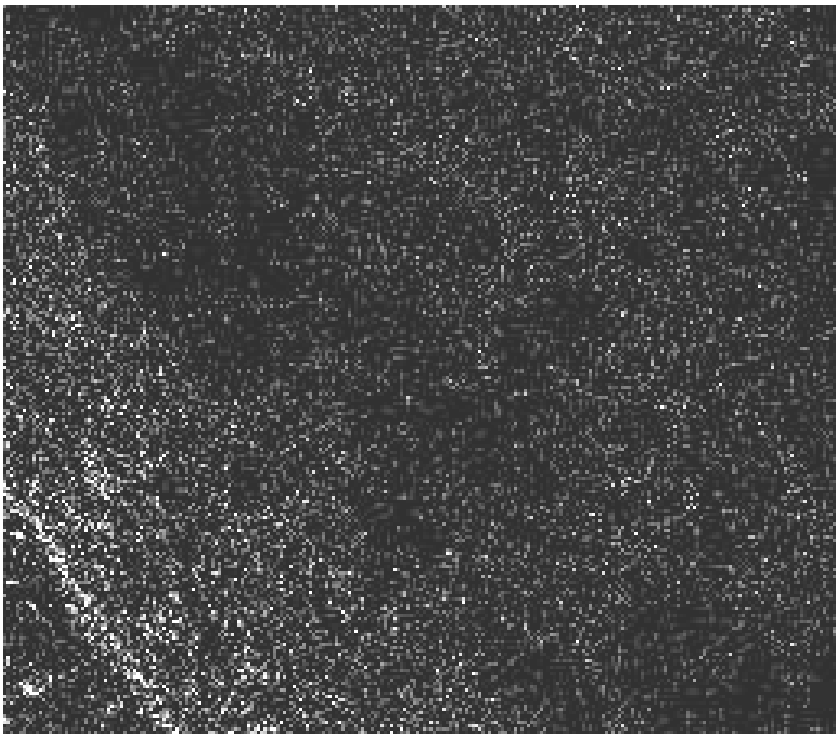


Figure 3.57b: X-ray map showing distribution of calcium (Ca Kα1) in sample UMF02

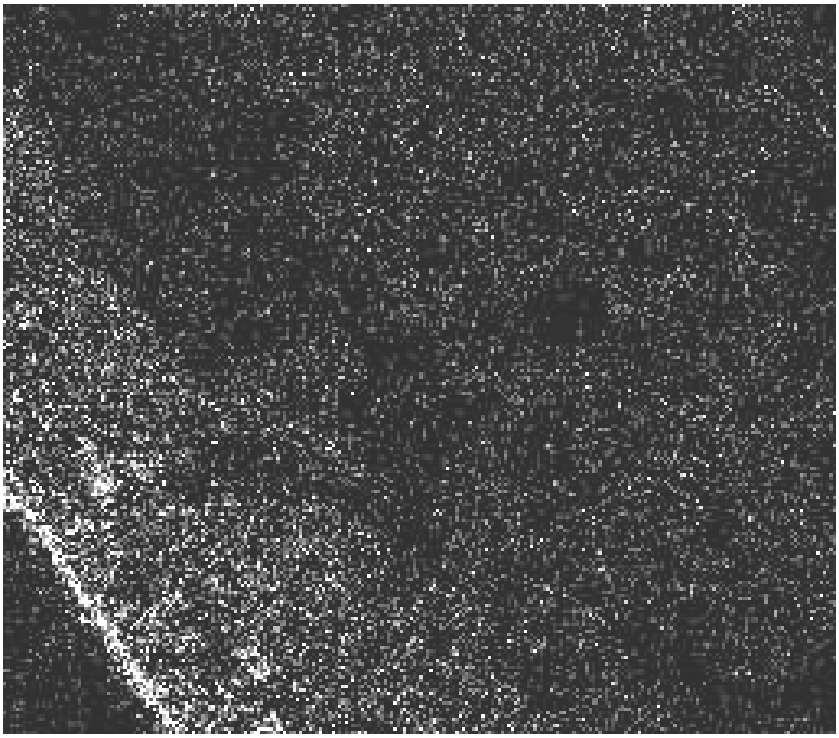


Figure 3.57c: X-ray map showing distribution of tin (Sn Lα1) in sample UMF02

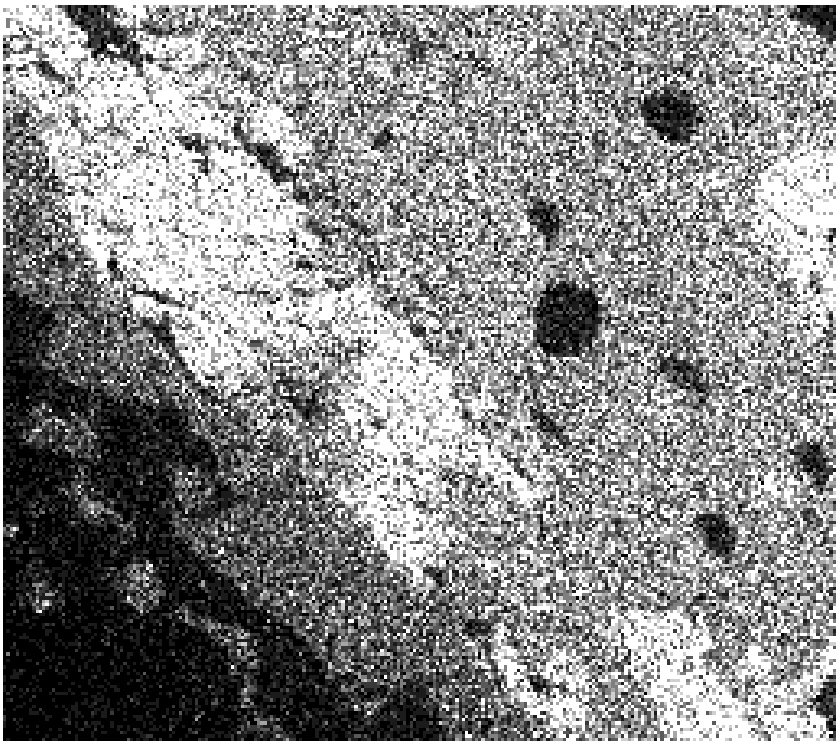


Figure 3.57d: X-ray map showing distribution of silicon (Si Kα1) in sample UMF02

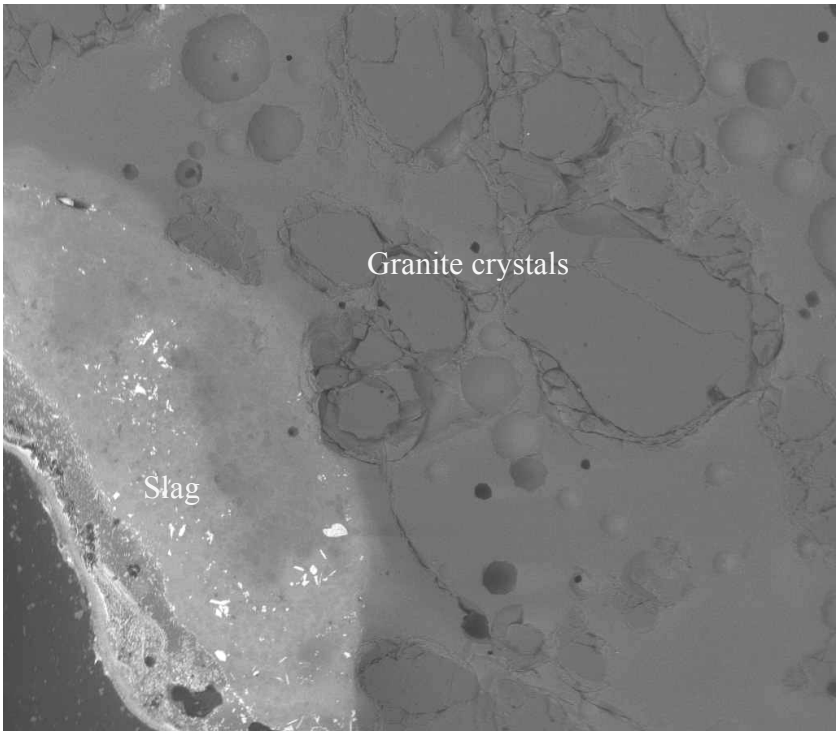


Figure 3.58a: SEM image of sample UMF02, showing the mineral crystals making up the granite and a thin line of phased slag running diagonally across the bottom left of the image

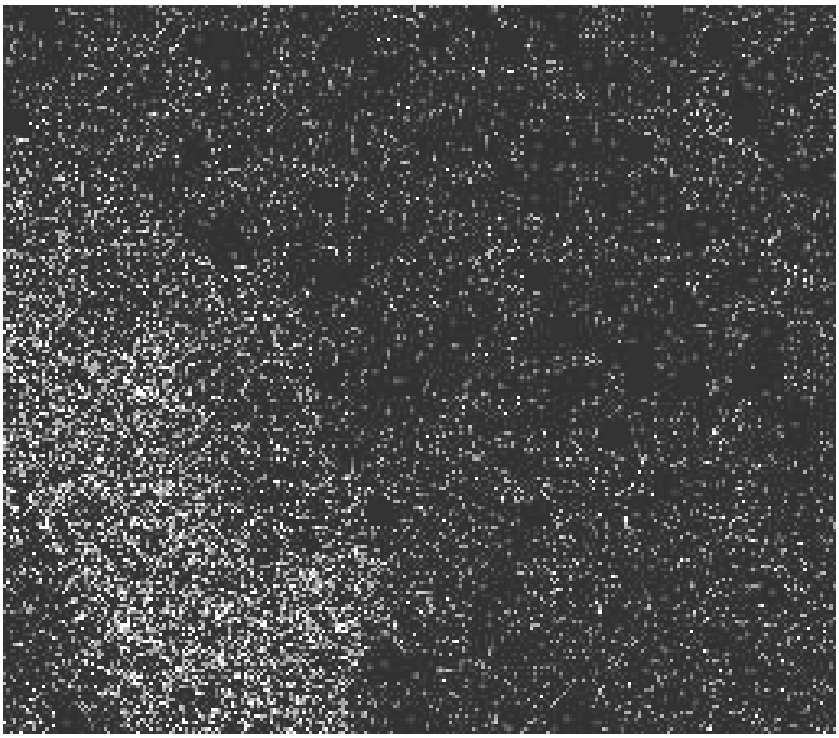


Figure 3.58b: X-ray map showing distribution of calcium (Ca Kα1) in sample UMF03

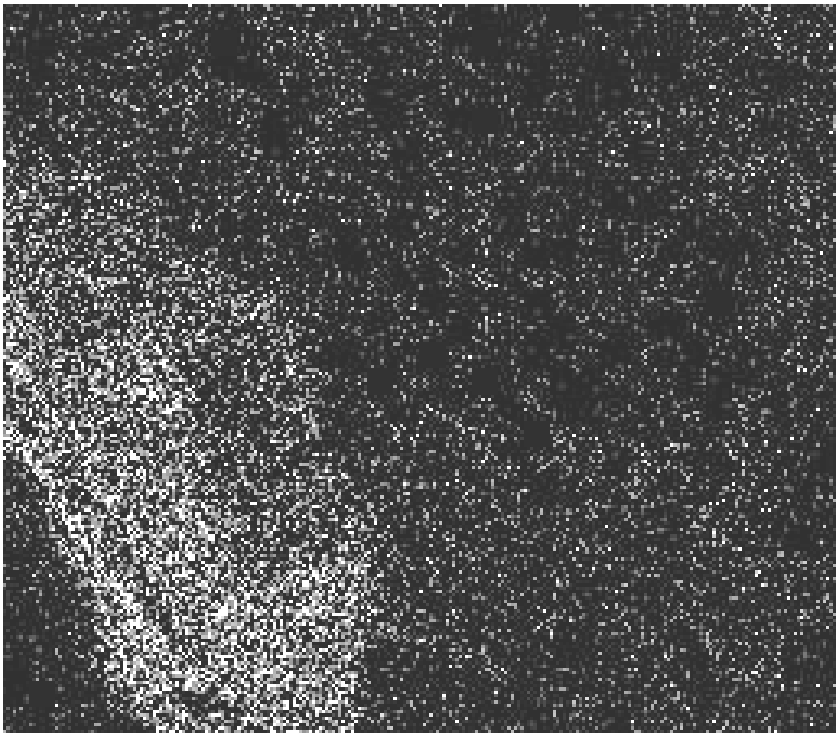


Figure 3.58c: X-ray map showing distribution of tin (Sn Lα1) in sample UMF03

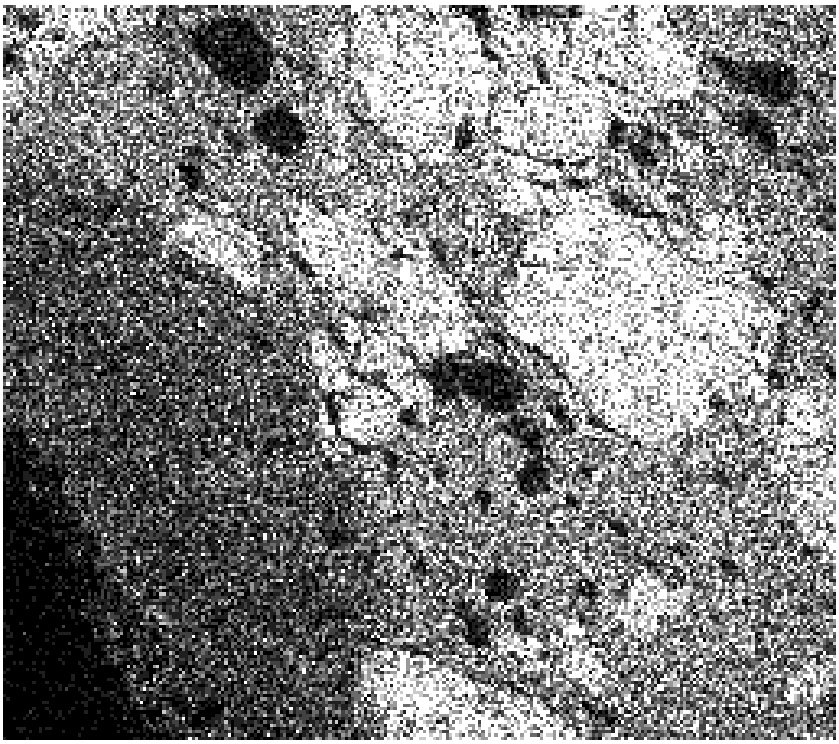


Figure 3.58d: X-ray map showing distribution of silicon (Si Kα1) in sample UMF03

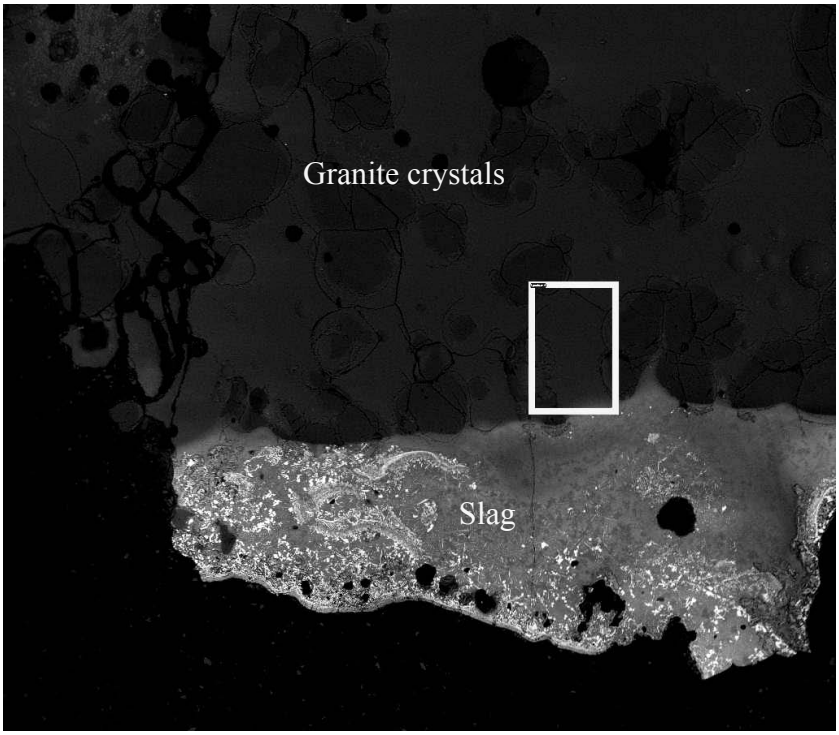


Figure 3.59a: SEM image of sample UMF02, showing the mineral crystals making up the granite and a line of phased slag running across the bottom of the image

Figure 3.59b: X-ray map showing distribution of calcium (Ca Kα1) in sample UMF04

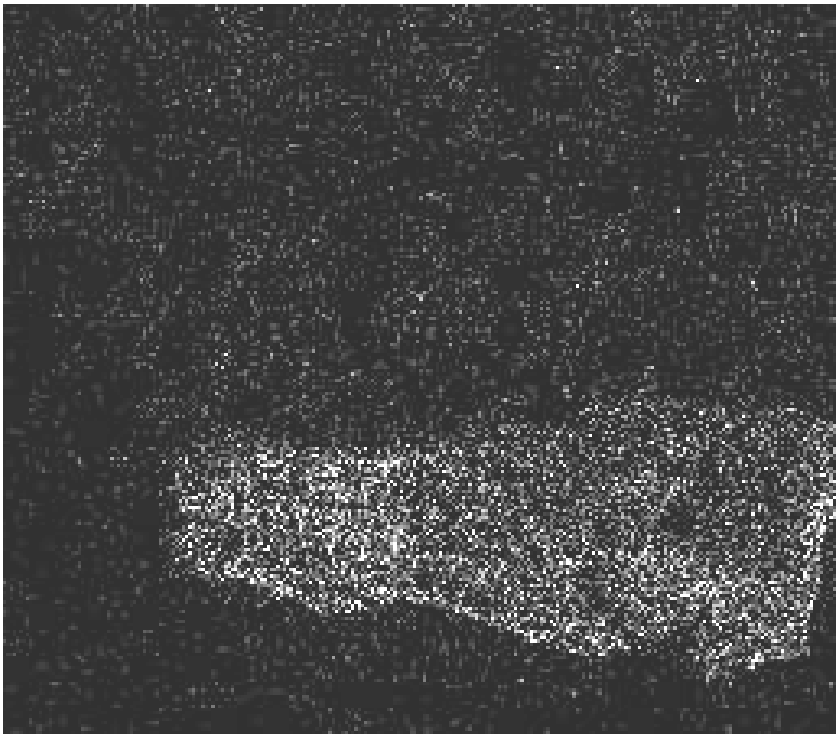


Figure 3.59c: X-ray map showing distribution of tin (Sn Lα1) in sample UMF04

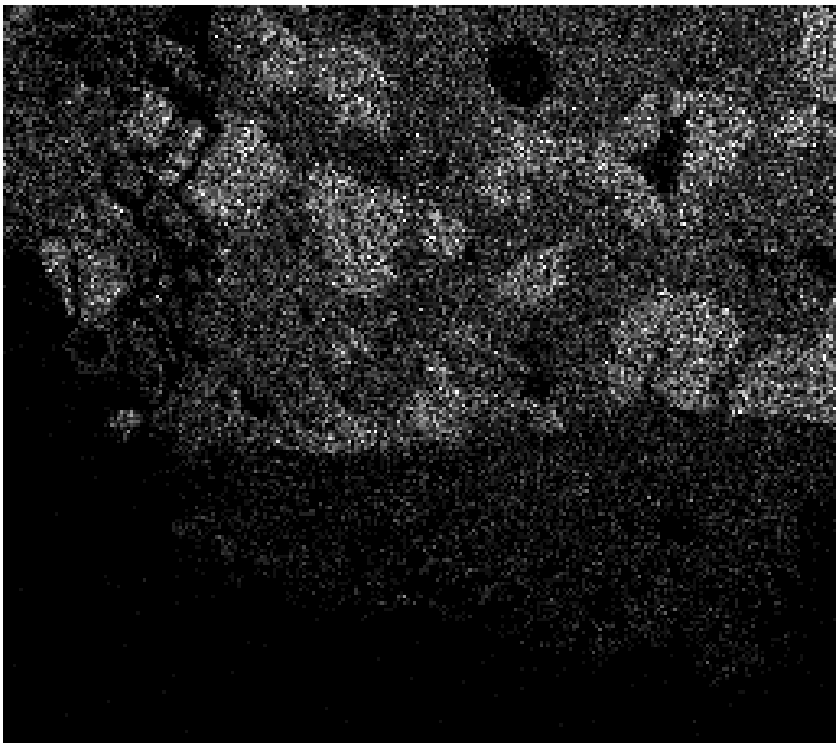


Figure 3.59d: X-ray map showing distribution of silicon (Si Kα1) in sample UMF04

3.3.3: Chemical Analysis of Furnace Materials

Energy dispersive X-ray spectra collected to provide qualitative compositional data for the four Upper Merrivale samples suggested that iron and titanium were present in the slag in relatively high proportions. The results of the fully quantitative compositional analysis carried out on Sample UMF02 are presented in Table 3.24. The area analysed is shown in Figure 3.60.

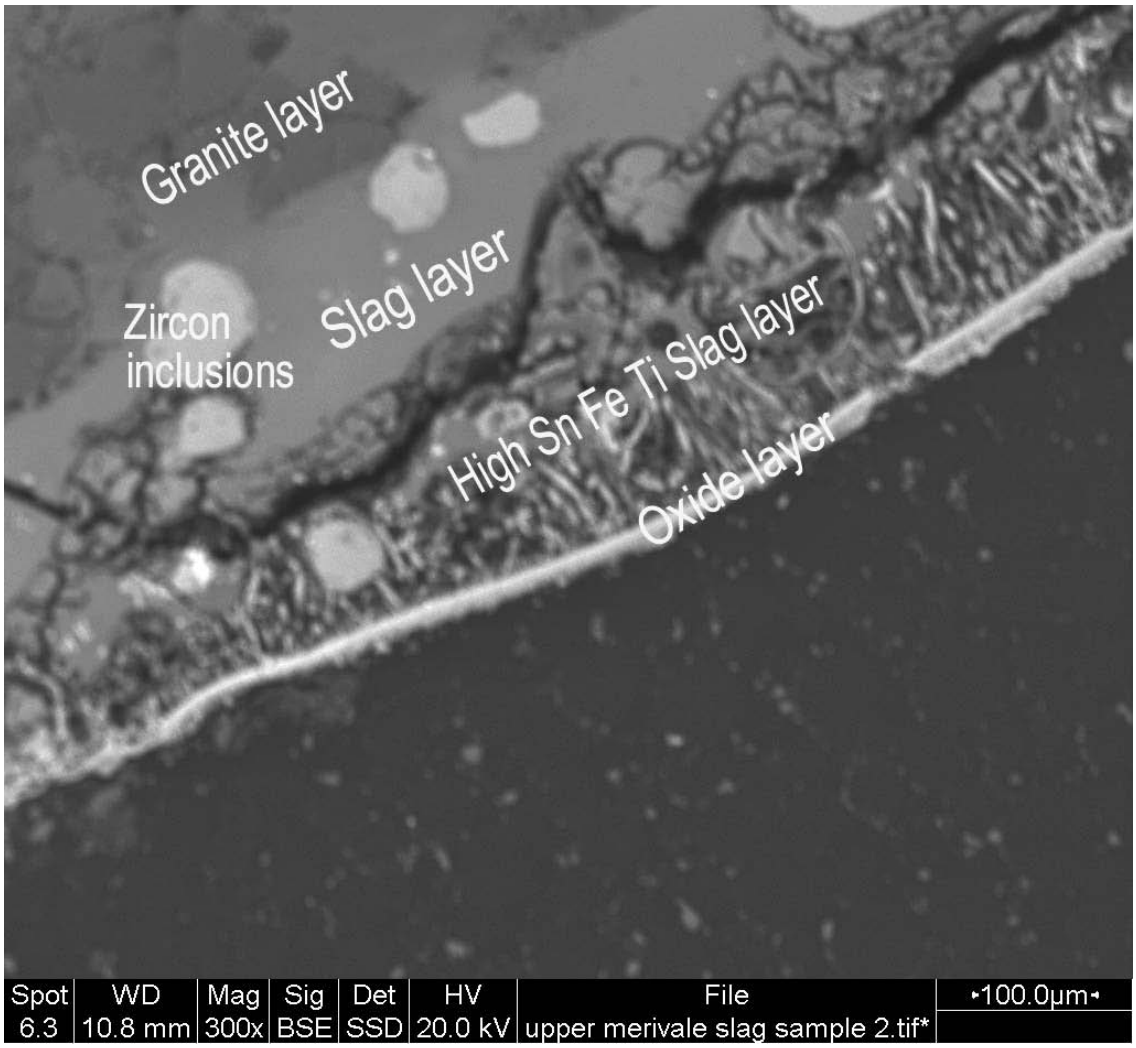


Figure 3.60: Backscattered electron image of Sample UMF02 showing outer oxide layer, dendritic phased slag layer, glassy slag layer and underlying granite layer.

Table 3.24: Chemical Composition (wt%) of Slag Layer on Furnace Wall material from Upper Merrivale, Sample UMF02, determined by EDX-SEM nd = not detected

Oxide	Oxide layer	Dendritic slag area	Matrix of glassy slag area	Pale inclusion in glassy slag layer	Bulk composition of granite layer	Quartz in granite layer	Feldspar? in granite layer
Na_2O	nd	0.34	1.97	0.06	3.71	0.04	4.43
MgO	1.62	0.71	2.59	0.12	0.03	nd	nd
Al_2O_3	1.14	2.87	12.97	nd	14.57	nd	17.51
SiO_2	0.63	6.69	47.77	33.71	75.22	103.06	70.68
P_2O_5	0.14	1.14	1.35	nd	0.22	0.20	0.32
K_2O	nd	0.15	2.04	0.01	6.20	0.03	7.37
CaO	0.19	nd	0.33	nd	0.31	nd	0.31
TiO_2	3.28	7.99	3.44	0.02	0.08	0.04	0.07
V_2O_5	0.09	0.55	0.05	0.08	0.01	nd	nd
MnO	0.08	0.16	0.25	nd	nd	0.02	0.02
FeO	28.83	20.43	13.80	0.19	1.35	nd	1.03
CuO	nd	nd	nd	nd	nd	nd	0.06
As_2O_3	nd	0.12	0.06	0.05	0.10	0.06	0.08
ZrO_2	0.70	6.21	2.88	63.37	nd	nd	nd
MoO_3	nd	0.68	0.15	0.16	0.18	0.10	nd
SnO	63.72	48.86	8.86	0.03	0.24	0.11	0.38
Sb_2O_3	nd	nd	nd	0.02	nd	nd	nd
WO_3	0.59	3.10	1.30	1.14	nd	nd	nd
Sum	101.01	100	99.81	98.96	102.22	103.66	102.26

These data indicate that the outer surface of the sample is coated with a c.25 μm thick layer of tin and iron oxides. Immediately underlying this is a layer of slag just over 100 μm thick that is extremely rich in tin and contains very high levels of iron and titanium. The composition of this area is not typical of smelting slags from this site. Backscattered electron imaging shows the microstructure of the slag in this area is dendritic. Beyond this is a layer of slag with a glassy microstructure, which has a composition more typical of other slags from this site. Within this glassy slag zirconia inclusions persist as a paler phase. Finally, there is a layer of granite, in which crystals of quartz can be observed. Bulk analysis of the granite layer indicates silica and alumina as major components. Analysis of individual phases confirms the presence of quartz and also suggests alkali feldspar.

The results of the fully quantitative SEM analysis carried out on the slagged clay from Godolphin in order to resolve its nature and determine whether it derived from a blowing house, are presented in Table 3.25. The sample was rich in arsenic, iron, aluminium and silicon, with some sodium, magnesium and potassium. Tin is a very minor constituent.

Semi-quantitative data from the slagged surface of the clay slab, collected using ICPMS, is given in Table 3.26, and confirms the results from the SEM analysis, i.e. that the most abundant elements present are arsenic and iron, though aluminium, silicon, calcium, copper and tin are also present, in addition to lesser amounts of sodium, magnesium, phosphorus, sulphur, titanium, barium, tungsten and lead. The precise composition of the reddish layer cannot be determined with ICPMS owing to the fact that it is so thin; there is likely to be interference from the clay itself.

Table 3.25: Chemical Composition (wt%) of Possible Slag Layer on Clay Slab from Godolphin, determined by EDX-SEM

Oxide	Area 1	Area 2	Area 3	Mean
Na_2O	1.1	0.9	1.5	1.2
MgO	3.8	2.2	1.9	2.6
Al_2O_3	15.5	12.9	15.7	14.7
SiO_2	15.6	26.4	25.7	22.6
P_2O_5	0.9	0.4	0.6	0.6
K_2O	1.7	1.7	3.7	2.3
CaO	6.7	4.8	3.7	5.1
TiO_2	0.5	0.6	0.4	0.5
V_2O_5	nd	nd	nd	nd
MnO	0.1	nd	0.2	0.1
FeO	21.3	20.0	15.2	18.8
CuO	0.2	0.2	0.1	0.2
ZnO	nd	0.1	0.1	0.1
As_2O_3	31.2	28.9	30.0	30.0
ZrO_2	nd	0.4	nd	0.2
MoO_3	0.3	0.4	0.3	0.4
SnO	0.7	nd	0.6	0.4
Sb_2O_3	0.4	0.2	0.4	0.3
WO_3	0.2	0.1	nd	0.1
Sum	100.0	100.2	100.2	100.2

nd = not detected

Table 3.26: Chemical Composition (ppm) of Possible Slag Layer on Clay Slab from Godolphin, determined by Laser Ablation ICP-MS

Run	7Li	9Be	11B	23Na	24Mg	27Al	29Si	31P	33S	39K	44Ca	45Sc	47Ti	51V	52Cr
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
1a	50	2	37	258	757	3042	2541	274	282	736	1382	2	170	6	8
1b	74	2	80	321	784	3390	3071	280	pnq	865	1175	3	274	8	10
1c	122	3	73	492	978	3664	3400	375	53	952	1330	3	258	9	13
Mean	82	2	63	357	840	3365	3004	310	112	851	1296	3	234	8	11

55Mn	56Fe	59Co	60Ni	65Cu	66Zn	69Ga	72Ge	75As	82Se	85Rb	88Sr	89Y	90Zr	93Nb	95Mo	101Ru	103Rh
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
63	7104	16	26	692	38	5	0	6144	0	15	71	11	39	10	4	0	0
85	9733	24	26	1100	61	5	0	7712	0	21	66	14	78	29	5	0	0
116	11580	27	38	1826	91	7	1	10440	0	23	74	17	60	19	6	0	0
88	9473	22	30	1206	63	5	0	8097	0	20	70	14	59	19	5	0	0

105Pd	107Ag	111Cd	118Sn	121Sb	125Te	133Cs	137Ba	139La	140Ce	141Pr	146Nd	147Sm	153Eu
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
0	2	0	1657	5	0	3	475	13	28	4	17	4	1
0	3	1	4894	9	0	4	496	18	39	6	22	6	1
0	4	1	3431	9	0	5	638	19	42	6	24	7	2
0	3	1	3327	8	0	4	537	17	36	6	21	6	1

157Gd	159Tb	163Dy	165Ho	166Er	169Tm	172Yb	175Lu	178Hf	181Ta	182W	185Re	189Os	193Ir	195Pt	197Au
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
5	1	4	1	2	0	2	0	3	8	120	0	0	0	0	0
6	1	5	1	3	0	3	0	6	28	247	0	0	0	0	0
7	1	6	1	3	0	3	0	4	16	246	0	0	0	0	0
6	1	5	1	3	0	3	0	4	17	204	0	0	0	0	0

202Hg	205Tl	208Pb	209Bi	232Th	238U
ppm	ppm	ppm	ppm	ppm	ppm
65	0	102	22	9	11
81	0	140	31	10	14
95	0	195	49	12	19
81	0	145	34	10	15

pnq = present not quantifiable

3.4: Results of Metallic Tin Analysis

3.4.1: Description of Metallic Tin Samples

All the samples of tin metal were irregularly shaped, and were clearly not cast ingots. Dimensions, masses and the appearance of the samples are recorded in Table 3.27.

Table 3.27: Description of Tin Metal Samples

Site	Sample No	Mass (g)	Size (cm)	Description
Carloggas / St Mawgan in Pyder	4/29	5.5	1.5 x 1.0 x 1.0	An irregular fragment with flattish sides. The upper and lower faces are weathered to a cream colour. Three other faces are dark grey, with some very small black crystals visible in places. The sample is non-magnetic.
Upper Merrivale	4/32	162.0	5.0 x 4.0 x 1.5	A sub-rounded lump with a pale grey crust. The crust appears to be laminated. One narrow edge is unnaturally flat as though it has solidified against a flat surface. This portion is less corroded. The sample broke into several pieces, revealing a darker grey sub-metallic interior approximately 0.5cm thick. Non-magnetic.
Upper Merrivale	4/33	8.0	2.0 x 3.0 x 1.0	A sub-rounded lump composed of a pale grey material. Non-magnetic.
Trevellas Porth, St Agnes	3/46	9.1	2.0 x 1.5 x 0.75	An irregular shaped dark grey nodule with some pitting on the surface. It was coated in places with a reddish-brown substance. When sectioned to reveal the interior, bright flakes of metal were observed, along with some slightly darker flakes. A crust of darkish-grey, which was probably a corrosion product, surrounded the flakes in the central portion of the sample. Non-magnetic.
Trevellas Porth, St Agnes	4/31	11.0	2.0 x 2.0 x 1.0	An irregular nodule of corroded metal, mid-grey in colour with iron staining and a small amount of white encrustation. The surface appears to consist of a series of lamellar flakes. Non-magnetic.

All the samples have suffered some corrosion to a greater or lesser extent: the outer portions of the Upper Merrivale samples appear to be fully oxidized, being composed

of a white/pale cream material. However, it seems clear that full re-oxidization of the inner portion of the larger of the two samples from Upper Merrivale (4/32) has not yet occurred, although the metal was extremely brittle. It is possible that some metal also remains in the centre of the smaller sample (4/33), although this could not be determined without sectioning it. Both were extremely friable. The bulk of the Carloggas sample was dark grey, so the fact that the white/cream crust was limited to just two opposing faces suggests this sample was only a part of an originally much larger specimen. (The identification of the sample from Carloggas/St Mawgan in Pyder is problematical. The original report of the excavation (Threipland 1956) refers to finds of tin slag, but subsequent analysis of material from this site suggests that this was in error and later reports refer to a sample that is either partially reduced ore or highly corroded tin metal. It is probable that sample 4/29 is similar to the fragments mentioned by Beagrie (1983) and is part of a corroded tin ingot.) Both samples from Trevellas Porth were more solid and appeared darker in colour than the metallic tin samples from the other sites, i.e. they appeared to have undergone less oxidation, although in both cases a thin layer of surface encrustation was visible.

3.4.2: Optical Microscopy of Metallic Tin Samples

Only a single sample, 3/46 from Trevellas Porth, was suitable for examination with an optical microscope. A grey crust of corrosion product could be seen around the edge of the sample (Figure 3.61). On closer examination, this crust was seen to consist of two layers of distinct appearance. The second type of material appeared white rather than grey, and formed a series of very narrow layers within the innermost part of the crust.

Normal electron beam imaging does not distinguish well between the different types of silicate minerals from which granite is composed, but it appears from the distribution of silicon as revealed by X-ray mapping (see Figures 3.56d, 3.57d, 3.58d and 3.59d) that the individual crystals remain discrete from one another within the vitrified layer. The slightly rounded edges of the crystals may indicate partial melting of the crystals.

Figures 3.56 to 3.59 are normal beam scanning electron micrographs of the furnace wall samples accompanied by X-ray maps of the same area. X-ray maps were obtained for calcium (Ca Kα1), tin (Sn Lα1) and silicon (Si Kα1).

As would be expected, tin appears to be most concentrated within the slag layer. The images apparently show calcium similarly distributed; however, the presence of high levels of tin in the slag is problematical since the Ca Kα1 X-ray peak is overlapped by the Sn $L_{\beta 1}$ peak; in this case, therefore, the technique will not provide a clear indication of the distribution of calcium within the samples.

The different mineral crystals making up the granite are distinguishable in the silicon maps as these minerals contain varying proportions of silicon (pure quartz is 100% silicon and thus appears brightest in the images).

Figure 3.62 shows the boundary between the crust and the central portion of the sample. The two types of crustal material can be seen forming layers in the lower part of the image.

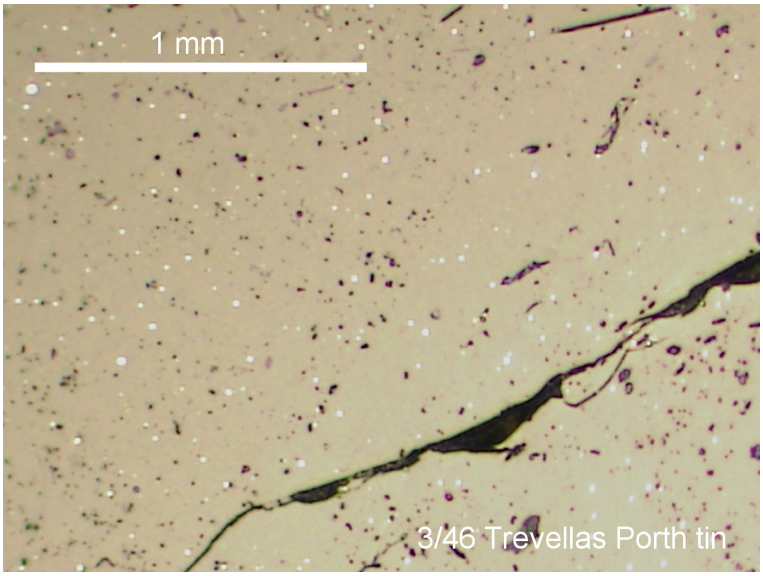


Figure 3.61: Outer part of corrosion crust around Trevellas Porth tin sample

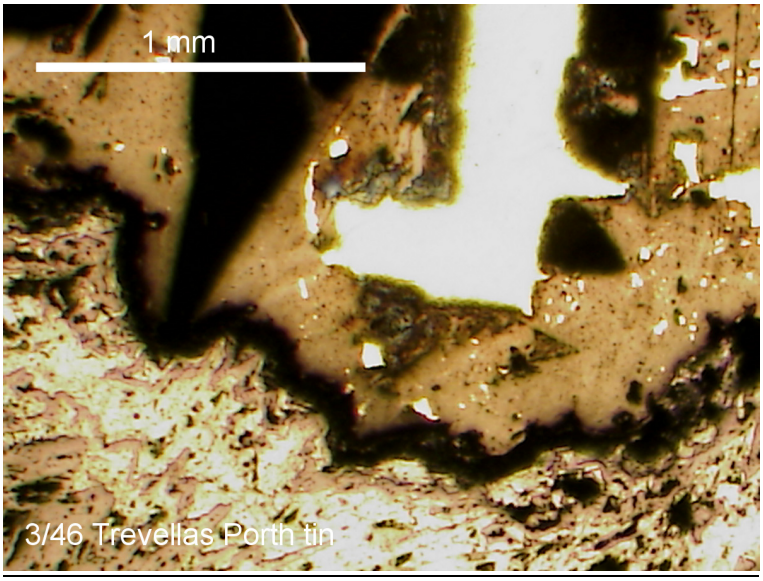


Figure 3.62: Boundary between crust (bottom) and central portion (top) of tin metal sample from Trevellas Porth. Two layers are visible within the crust.

The majority of the central portion of the sample also appeared to be starting to re-oxidize but some slivers of bright metal could be distinguished, along with some other areas that were unreflective (Figure 3.63).

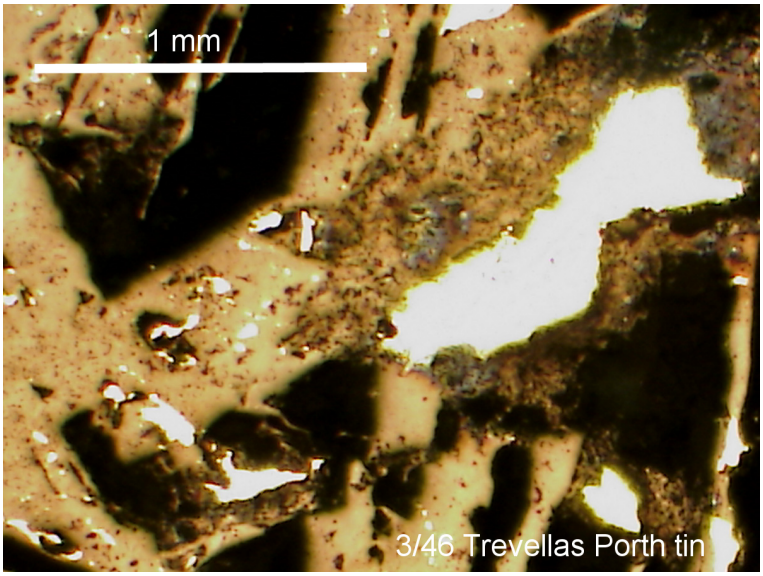


Figure 3.63: Central portion of Trevellas Porth tin sample, showing re-oxidized tin (grey), and metallic tin (white).

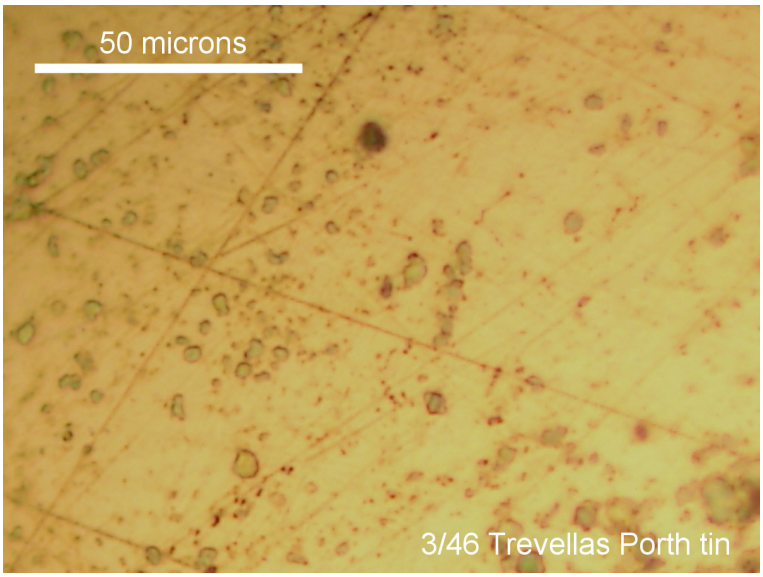


Figure 3.64: Tin metal from Trevellas Porth showing dark 'pocks' of impurities within the metal.

At high magnification the bright metallic flakes appeared to contain a few darker 'pocks' (Figure 3.64), the presence of which indicate that impurities are present in the metal.

3.4.3: Results of Chemical Analysis of Metallic Tin Samples

EDX-SEM Analysis

Only sample 3/46 was suitable for analysis using EDX-SEM. The scanning electron microscope was used to determine the chemical composition of the metal flakes contained within the central portion of the sample and also the corrosion layers surrounding them. Eight scans were made at 1000x magnification. Areas 1 to 4 covered the outer corrosion layer. Area 5 covered the inner corrosion layer. Areas 6 and 7 were darker flakes within the central portion of the sample. Area 8 was a bright metallic flake within the central portion. Additionally two spot scans were carried out at 1000x magnification on what appeared to be brighter and darker patches within the inner corrosion layer. Results are given in Table 3.28.

Areas 1 to 4 are very rich in tin oxide, indicating that the outer corrosion layer is composed largely of re-oxidized tin, with the count rate of the machine suggesting that tin oxide was present both in the form of SnO (romarchite) and as SnO_2 (cassiterite). As pure SnO is black and SnO_2 white, this may explain the different coloured bands within the outer corrosion layer. Small quantities of other elements are also present: metallic elements such as molybdenum and antimony may be impurities in the smelted tin; minor amounts of silica, sodium and calcium oxides probably derive from the burial environment, which contained sand and sea water. In addition, although chlorine was not sought by the analyser software, an X-ray peak for chlorine was observed in the

spectra for the corrosion layers, again probably deriving from immersion of the sample in sea water; the sample may thus contain some tin chloride.

Table 3.28: Chemical composition of Trevellas Porth tin determined by EDX-SEM (wt%)

	Outer Corrosion Layer				Inner Corrosion Layer			Dark Flake		Metal
Oxide	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Spot 1**	**Spot 2**	**Area 6**	**Area 7**	**Area 8**
Na_2O	0.2	0.5	0.3	1.1	0.4	0.4	0.3	0.6	0.4	0.5
MgO	0.1	nd	0.2	0.1	nd	nd	0.2	nd	nd	nd
Al_2O_3	0.1	0.1	0.1	0.4	nd	0.1	nd	0.1	nd	0.2
SiO_2	0.4	0.6	0.5	1.0	0.4	0.4	0.3	2.3	0.7	0.4
P_2O_5	nd	nd	nd	nd	0.1	0.1	nd	0.3	0.1	0.1
K_2O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
CaO	0.8	0.5	0.6	0.6	1.0	0.9	0.9	1.6	2.6	0.9
TiO_2	0.1	nd	0.2	0.2	0.2	0.1	0.2	nd	0.4	0.2
V_2O_5	nd	0.1	nd	nd	nd	nd	nd	0.1	nd	nd
MnO	0.1	0.1	0.1	nd	nd	nd	nd	nd	nd	nd
FeO	nd	0.2	nd	nd	nd	0.1	nd	0.3	nd	0.1
CuO	0.2	nd	nd	0.1	0.1	0.2	nd	1.7	1.3	nd
ZnO	0.1	0.1	nd	0.7	nd	0.1	nd	nd	0.1	nd
As_2O_3	0.1	nd	nd	nd	nd	nd	nd	2.9	1.7	0.2
ZrO_2	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
MoO_3	0.6	0.5	0.5	0.6	0.8	0.1	0.7	3.3	0.6	nd
SnO	95.9	97.1	98.8	94.7	96.5	97.5	93.7	85.4	89.7	99.2
Sb_2O_3	0.7	0.4	nd	0.6	0.7	nd	0.4	1.8	2.1	1.1
WO_3	0.2	nd	nd	nd	0.1	0.2	0.4	nd	0.7	nd
Total	99.7	100.4	101.2	100.1	100.3	100.1	97.1	100.4	100.4	102.9

nd = not detected

The inner corrosion layer, analysed as Area 5 and Spots 1 and 2, is not noticeably different in composition to the outer layer. The presence of brighter and darker patches within this layer appears to derive from a very small reduction in the amount of tin and slightly enhanced levels of molybdenum.

Within the central portion of the sample, two types of flake could be distinguished, one that showed dark, while the other was extremely bright. Two dark flakes were scanned as Areas 6 and 7. These were found to be lower in tin than other parts of the sample,

although tin remained the majority constituent. Other metallic elements were present in small quantities: antimony, arsenic, molybdenum and copper. Calcium and silicon also appear to be present, perhaps indicating that some slag remains mixed in with the metal.

Table 3.29: Chemical composition of metallic flakes in Trevellas Porth tin (wt%)

Element	Tin 1	Tin 2
Cl	1.5	0.4
Ti	nd	0.2
Mn	nd	nd
Fe	nd	0.1
Cu	0.1	nd
Zn	nd	nd
As	nd	nd
Mo	0.2	nd
Sn	101.0	99.4
Sb	nd	nd
W	nd	0.3
Total	102.8	100.2

nd = not detected

Area 8 appeared as a very bright patch, and contained tin with only small amounts of impurities, particularly calcium and antimony. The results indicated that the tin was likely to be present in metallic form rather than as tin oxide. Two further scans of this type of flake were subsequently made (Table 3.29) and show that trace levels of impurities such as iron, copper and tungsten are present. Traces of chlorine may indicate corrosion products formed in a salt-water environment.

Laser Ablation ICPMS

A single run was made to obtain compositional data for the grey inner portion of Carloggas sample 4/29. Data was obtained for the metallic inner portion of Upper Merrivale sample 4/32, and also its outer corrosion layer. Only the corrosion layer of

sample 4/33 from Upper Merrivale was analysed. Four runs were carried out for sample 3/46 from Trevellas Porth: two of the outer corrosion layer and two of flakes in the interior portion of the sample. The machine was unable to collect data for the interior portion as too much tin entered the system. Two runs were made to obtain data from different points across the surface of the second sample from this site, 4/31.

A mean of the results is provided in Table 3.30 and full data in Appendix 11. A summary of the results is given in Table 3.31.

Table 3.31: Summary of ICPMS results for Tin Metal samples

Sample	Run	Most abundant elements	Minor elements
Carloggas 4/29	1	Sn	Fe Hg
Upper Merrivale 4/32 (inner)	1	Sn	Bi
Upper Merrivale 4/32 (outer)	2	Sn	Al Si Fe
Upper Merrivale 4/33 (outer)	1	Sn Al K Fe	B Na Mg K
Trevellas Porth 3/46 (outer)	1	Sn	Mg Zn
Trevellas Porth 3/46 (outer)	2	Sn	Zn
Trevellas Porth 4/31 (outer)	1	Sn	Fe
Trevellas Porth 4/31 (outer)	2	Sn	Fe

The Carloggas sample is mainly composed of tin, but with traces of iron and mercury apparently present.

Likewise, the inner portion of Upper Merrivale sample 4/32 is almost pure tin, but does appear to contain trace amounts of metallic elements including copper, arsenic, antimony, mercury and bismuth.

The corrosion layers of both samples from this site are of more complex nature. Though mainly containing tin (as the oxide and dioxide, see XRD results below), the crust also contains quantities of elements such as aluminium, silicon and iron, in addition to trace amounts of many other elements. Almost certainly these are derived from the soil in which the samples lay.

Table 3.30: Mean Results of ICPMS Analysis of Tin Metal

Label	7Li ppm	9Be ppm	11B ppm	23Na ppm	24Mg ppm	27Al ppm	29Si ppm	31P ppm	33S ppm	39K ppm	44Ca ppm
Mean of Carloggas 4/29	0	0	0	pnq	8	51	77	25	pnq	66	72
Mean of Upper Merrivale 4/32 inner	0	0	0	pnq	0	1	pnq	0	pnq	46	pnq
Mean of Upper Merrivale 4/32 outer	1	5	2	pnq	22	607	258	92	pnq	64	pnq
Mean of Upper Merrivale 4/33 outer	13	1	517	150	227	1317	2730	54	pnq	407	19
Mean of Trevellas Porth 3/46 outer	2	2	47	2581	17210	1313	1255	614	41	1066	368
Mean of Trevellas Porth 3/46 outer	2	1	76	2843	4606	3163	3345	167	237	1124	729
Mean of Trevellas Porth 4/31 outer	0	30	26	2766	1444	2121	1523	527	pnq	1000	1089
Mean of Trevellas Porth 4/31 outer	0	32	15	2543	774	2469	1399	416	pnq	781	1134

Label	45Sc ppm	47Ti ppm	51V ppm	52Cr ppm	55Mn ppm	56Fe ppm	59Co ppm	60Ni ppm	65Cu ppm	66Zn ppm	69Ga ppm	72Ge ppm
Mean of Carloggas 4/29	0	4	0	1	9	274	3	4	2	4	0	0
Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	2	19	0	0	0
Mean of Upper Merrivale 4/32 outer	0	10	1	0	9	104	0	0	2	6	0	0
Mean of Upper Merrivale 4/33 outer	0	65	2	0	18	1120	0	0	1	5	2	0
Mean of Trevellas Porth 3/46 outer	0	69	39	30	61	1890	6	45	2696	45610	1	0
Mean of Trevellas Porth 3/46 outer	0	50	24	9	57	6766	3	22	681	13080	1	0
Mean of Trevellas Porth 4/31 outer	8	306	35	69	112	37870	11	24	2544	8514	6	4
Mean of Trevellas Porth 4/31 outer	10	998	33	51	145	33230	11	21	2424	7626	3	1

Label	75As	82Se	85Rb	88Sr	89Y	90Zr	93Nb	95Mo	101Ru	103Rh	105Pd	107Ag
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Mean of Carloggas 4/29	1	0	0	2	0	0	0	0	0	0	0	22
Mean of Upper Merrivale 4/32 inner	43	0	0	0	0	0	0	0	0	0	0	0
Mean of Upper Merrivale 4/32 outer	6	0	1	1	2	1	0	0	0	0	0	0
Mean of Upper Merrivale 4/33 outer	5	0	11	7	2	4	4	0	0	0	0	0
Mean of Trevellas Porth 3/46 outer	414	0	4	19	4	4	0	9	0	0	0	85
Mean of Trevellas Porth 3/46 outer	100	0	6	31	3	3	0	4	0	0	0	23
Mean of Trevellas Porth 4/31 outer	531	0	2	44	38	86	39	3	0	0	0	20
Mean of Trevellas Porth 4/31 outer	490	0	2	47	41	845	24	2	0	0	0	14

Label	111Cd	118Sn	121Sb	125Te	133Cs	137Ba	139La	140Ce	141Pr	146Nd	147Sm	153Eu
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Mean of Carloggas 4/29	0	139800	0	0	0	3	0	0	0	0	0	0
Mean of Upper Merrivale 4/32 inner	0	83500	26	0	0	0	0	0	0	0	0	0
Mean of Upper Merrivale 4/32 outer	0	33480	1	0	1	3	2	3	1	4	1	0
Mean of Upper Merrivale 4/33 outer	0	3220	5	0	5	10	8	23	3	11	2	0
Mean of Trevellas Porth 3/46 outer	9	365800	6	1	1	13	5	4	1	7	2	0
Mean of Trevellas Porth 3/46 outer	7	399000	1	1	1	17	3	3	1	3	1	0
Mean of Trevellas Porth 4/31 outer	17	435900	4	1	0	23	84	39	23	122	30	7
Mean of Trevellas Porth 4/31 outer	14	370900	4	1	0	21	86	39	23	122	32	7

Label	157Gd ppm	159Tb ppm	163Dy ppm	165Ho ppm	166Er ppm	169Tm ppm	172Yb ppm	175Lu ppm	178Hf ppm	181Ta ppm	182W ppm	185Re ppm
Mean of Carloggas 4/29	0	0	0	0	0	0	0	0	0	0	0	0
Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	0	0	0
Mean of Upper Merrivale 4/32 outer	1	0	1	0	1	0	1	0	0	0	21	0
Mean of Upper Merrivale 4/33 outer	2	0	2	0	1	0	1	0	1	2	46	0
Mean of Trevellas Porth 3/46 outer	2	0	1	0	1	0	1	0	0	0	16	0
Mean of Trevellas Porth 3/46 outer	1	0	1	0	0	0	0	0	0	0	9	0
Mean of Trevellas Porth 4/31 outer	28	4	21	4	9	1	8	1	5	17	9244	0
Mean of Trevellas Porth 4/31 outer	29	4	23	4	9	1	8	1	42	4	3289	0

Label	189Os ppm	193Ir ppm	195Pt ppm	197Au ppm	202Hg ppm	205Tl ppm	208Pb ppm	209Bi ppm	232Th ppm	238U ppm
Mean of Carloggas 4/29	0	0	0	0	153	0	39	1	0	0
Mean of Upper Merrivale 4/32 inner	0	0	0	0	24	0	6	166	0	0
Mean of Upper Merrivale 4/32 outer	0	0	0	0	0	0	32	2	1	6
Mean of Upper Merrivale 4/33 outer	0	0	0	0	12	0	11	4	8	9
Mean of Trevellas Porth 3/46 outer	0	0	0	0	5945	0	826	56	3	4
Mean of Trevellas Porth 3/46 outer	0	0	0	0	2997	0	964	3	4	10
Mean of Trevellas Porth 4/31 outer	0	0	0	1	692	10	3635	77	15	16
Mean of Trevellas Porth 4/31 outer	0	0	0	0	1112	8	3127	56	60	22

pnq = present not quantifiable

The corrosion layers of the samples from Trevellas Porth are extremely rich in tin, but iron is also relatively abundant, raising the possibility that the tin is less than pure and may contain some of the tin-iron alloy hardhead. However, as it was not possible to determine the composition of the inner portion of these samples, it cannot be stated whether the iron and other less abundant elements were present as impurities in the smelted tin metal or whether these derived from the burial environment. Molybdenum, detected using SEM, was not confirmed using this method.

X-ray Diffraction

X-ray spectra for the samples from Carloggas and Upper Merrivale are shown in Figures 3.65 to 3.67. Ideal spectra for the minerals stated are superimposed on the spectra of the ores to aid comparison. A summary of the minerals identified using XRD is shown in Table 3.32.

Table 3.32: Summary of X-ray Diffraction results for Tin Metal samples

Sample	Major minerals
Carloggas 4/29	Romarchite
Upper Merrivale 4/32	Cassiterite, Romarchite

The metal samples from Upper Merrivale are shown to have undergone oxidation to both romarchite (SnO) and cassiterite (SnO_2). Although the pale corrosion layer on some faces of the Carloggas sample suggested that cassiterite was present, material for analysis was taken from the inner portion and this contained only romarchite. If metallic tin remains in any of these samples, it is in quantities insufficient for it to be positively identifiable by this method.

Figure 3.65: XRD Spectrum of Carloggas sample (Romarchite)

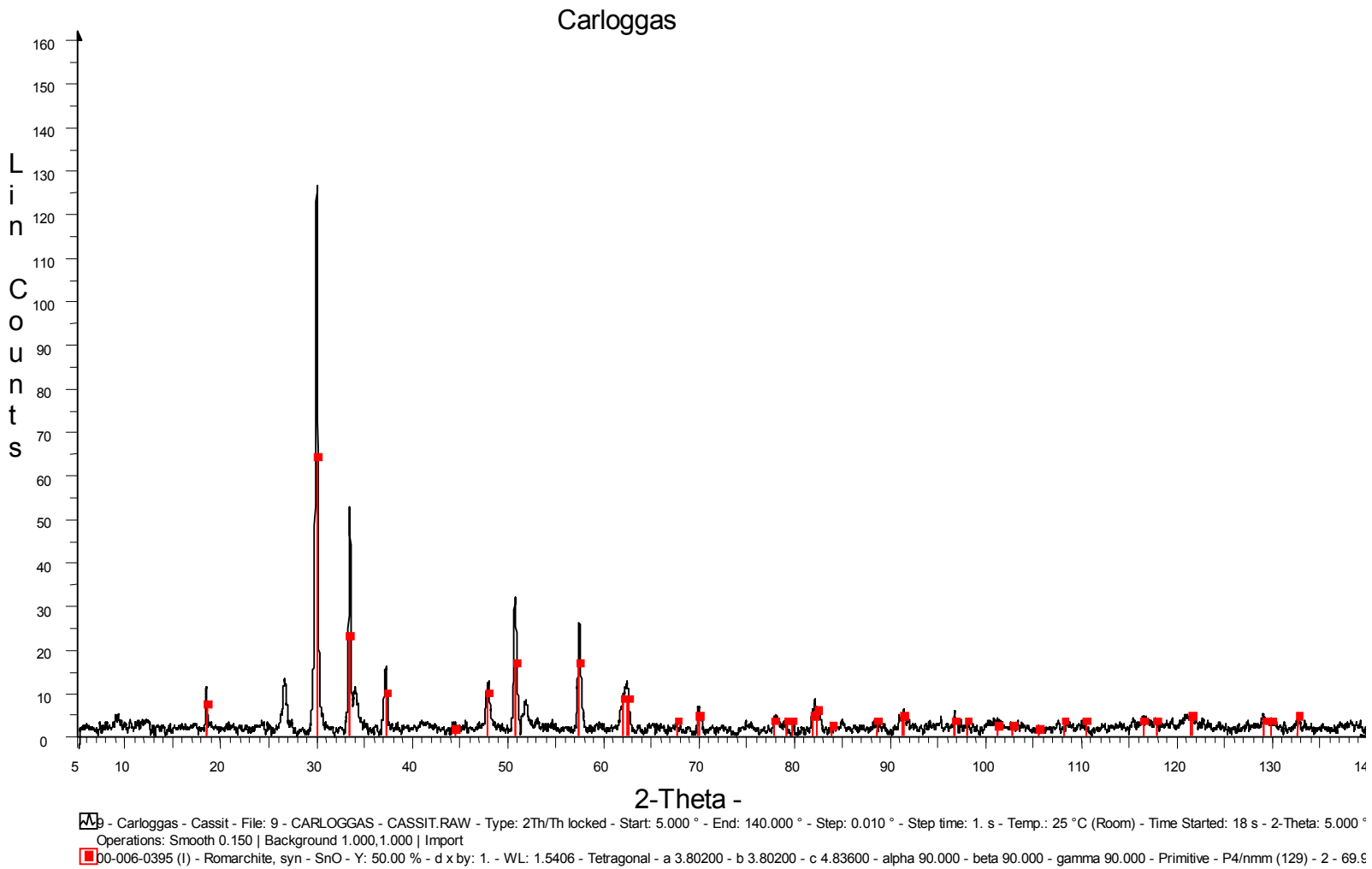


Figure 3.66: XRD Spectrum of Upper Merrivale sample 4/32 metallic tin (Cassiterite)

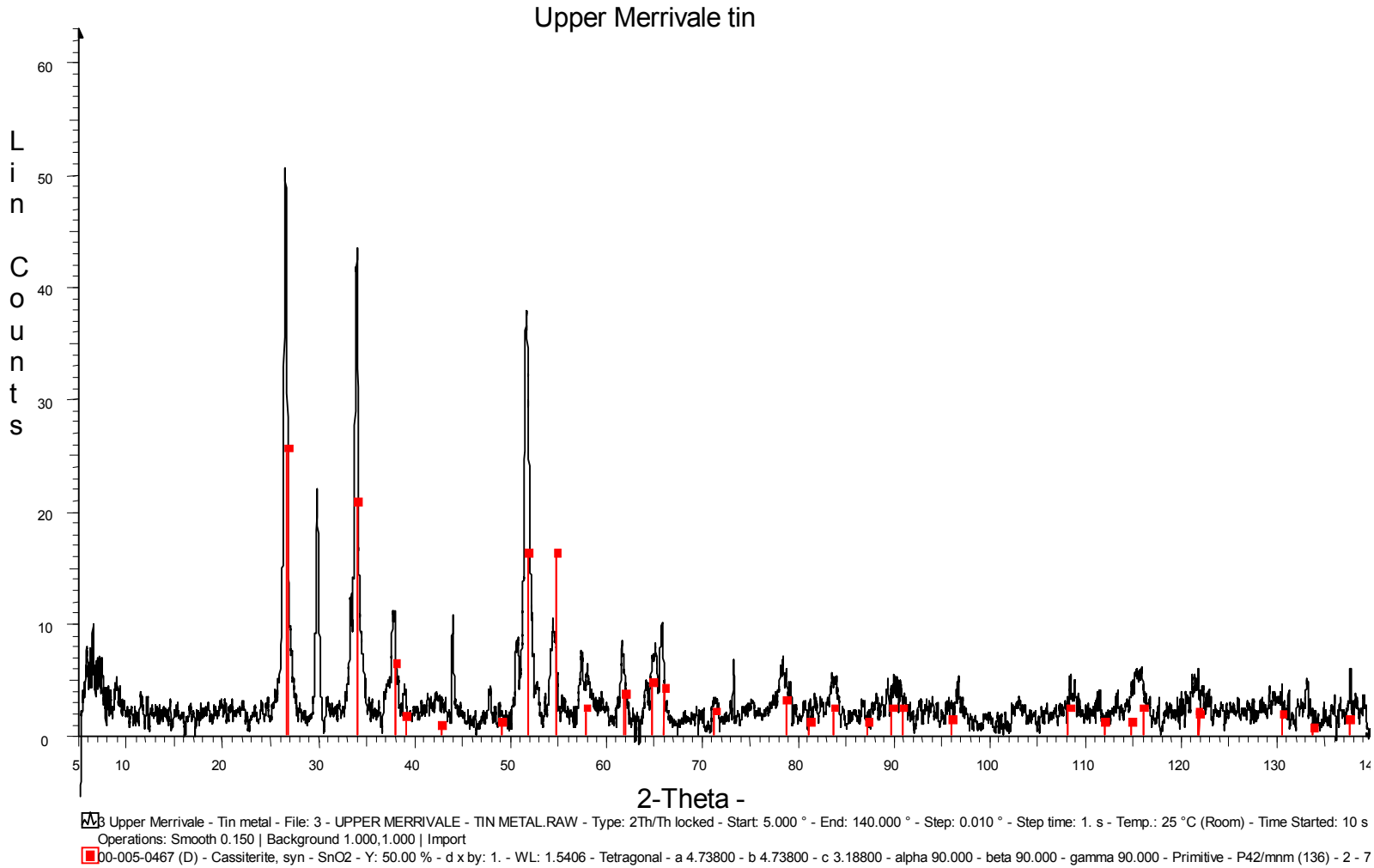
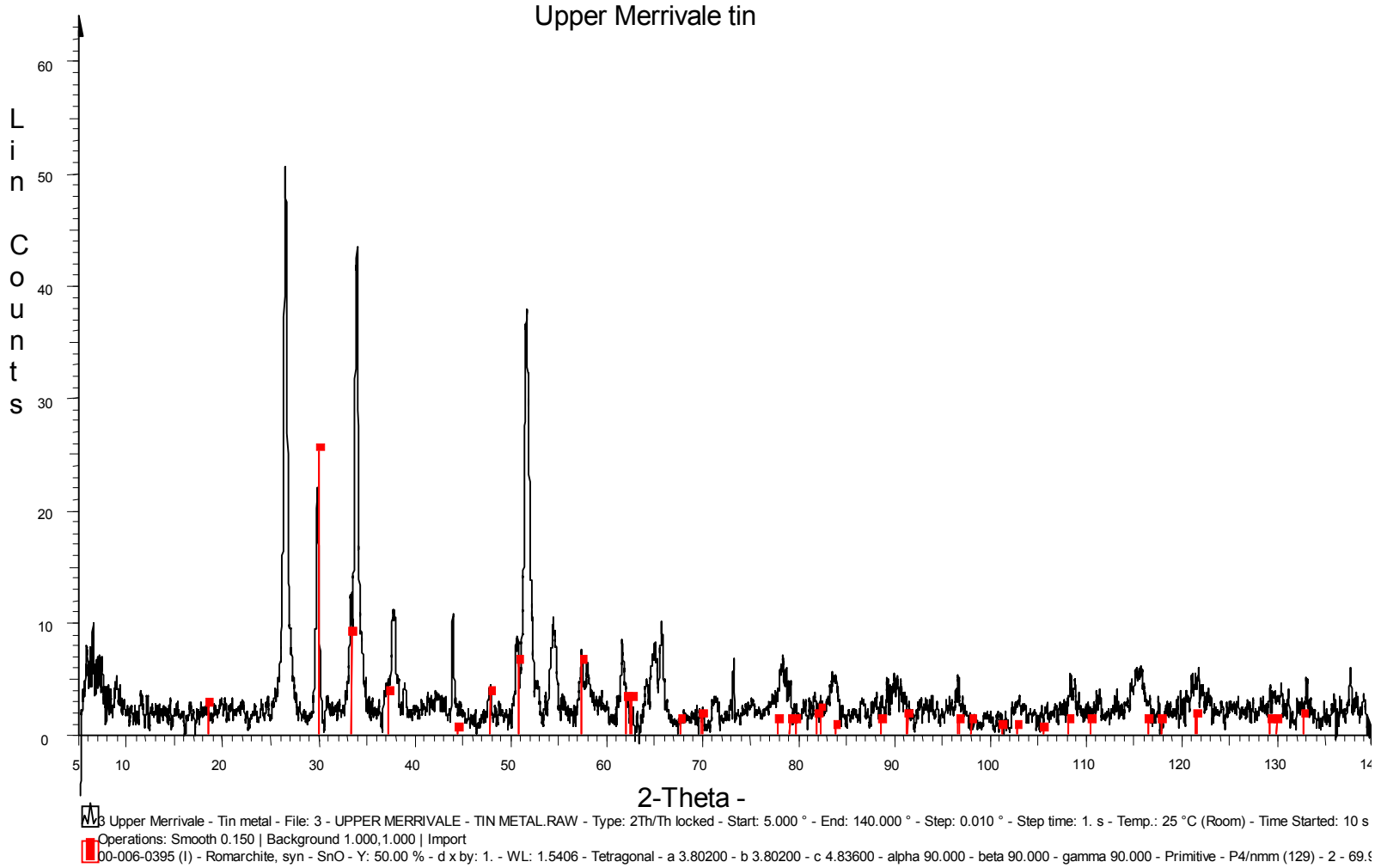


Figure 3.67: XRD Spectrum of Upper Merrivale sample 4/32 metallic tin (Romarchite)



3.4.4: Summary of Tin Metal Analysis

The sample from Carloggas is most closely matched with the spectrum of romarchite, SnO, a black mineral that would account for the dark colour of the inner portion of the material. The nature of specimen is difficult to ascertain: it is either partially reduced cassiterite or partially oxidized tin metal, however its regular shape and the more advanced state of oxidation upon two faces suggests the latter: it is probably a fragment of a highly corroded ingot.

The high tin content determined by the ICPMS analysis suggests metal of superior quality, but considering that the major impurity appears to be iron, which has a large margin of error associated with it, such measurements would require confirmation using other techniques. The possibility of contamination must also be considered, as the fragment was stored with other finds from the same site including iron slags.

The samples from Upper Merrivale are heavily corroded to a mixture of SnO and SnO_2, and the oxidation layer appears to contain many elements that are likely to have derived from the burial environment. However, the inner portion of at least one sample has not yet undergone full re-oxidation, and the metal appears to be tin of high quality, containing only trace levels of a few metallic elements. The irregular shape of the pieces of tin metal from Upper Merrivale and the location in which they were found indicate that these are examples of metal that has escaped through the bottom of the furnace, and their composition therefore reflects the unrefined product of the smelt.

The samples from Trevellas Porth were both small irregular shaped drops and thus, like the Merrivale samples, are probably tin that has escaped through the base of the furnace. Although the surfaces were encrusted with a layer of corrosion product, these

were relatively thin compared to specimens from other sites. (Given that the samples from Upper Merrivale and Trevellas Porth may be considered to be of roughly similar age, the difference in the extent of corrosion is interesting.) The corrosion layer, composed mostly of tin oxide, appears also to have incorporated elements from the burial environment.

The sectioned sample from this site consisted of grains of uncorroded tin metal, some of which also contained impurities including iron, tungsten and arsenic: these impurities appeared as pocks of alloy within the flakes of pure tin.

THE CLASSIFICATION AND INTERPRETATION OF TIN SMELTING REMAINS FROM SOUTH WEST ENGLAND

A study of the microstructure and chemical composition of tin smelting slags from Devon and Cornwall, and the effect of technological developments upon the character of slags.

Volume II of II

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Chapter 4

Discussion

4.1: Slag Analysis

Analysis was carried out in order to determine the relationship between the chemical composition and the physical appearance of tin slags, and subsequently to relate the observed characteristics to changes in smelting technology. In all the following discussions it should be borne in mind that furnace conditions vary greatly during the course of a smelt and that the samples examined may have formed in different parts of a furnace and at different times during the process; slag recycling may also have occurred (see Section 4.1.3).

4.1.1: Factors Determining the Appearance of Slag

4.1.1.1: Morphology, Microstructure and Viscosity

When examining slags by eye, the following characteristics may be noted: colour, morphology, lustre and the presence of inclusions. All slags are dark in colour, owing to the presence of iron and magnesium; however in samples with lower levels of mafic minerals the colour tends to be dark brown rather than black. The shape of the sample depends largely upon the viscosity of the slag but may also be influenced by how the slag is treated during the smelting process. The scraping of thin sheets of slag from the surface of the molten metal could result in the formation of arc-shapes. Rod-like morphologies may be produced when molten slag is ladled out of the float and then poured away. Smerdon (1997) suggests that the curved shape of pieces of slag found at Avon Dam blowing house could mean that the tuyère was an

iron pipe; while slag could have solidified around the blast-cooled tuyère, this theory is as yet unconfirmed.

The lustre of any sample may be glassy, silky or matt, and is determined by the microstructure of the slag: glassy lustre owing to a lack of crystal phases and at the other extreme matt lustre resulting from the presence of large crystals. Finally, within the slag, two types of inclusion may be observed: there may be prills of metal, trapped when the slag solidified; additionally, a variety of different mineral species, which are derived either from the ore or possibly the furnace lining material, may persist as crystals within the slag (see Section 4.1.1.2 below).

Even at this most basic level it is clear from the samples examined that there is no simple relationship between the appearance of a piece of slag and the technology that produced it: witness the rod-like morphologies of some glassy blowing house slags, similar to much earlier slags, and the large matt slabs of slag from others, similar to reverberatory slags. Appearance is a consequence of the viscosity and microstructure of the slag, and this is not directly related to the age of the sample.

Viscosity in slags is determined by two factors: temperature and the chemical composition. Unfortunately, the temperature at which various types of furnace in antiquity operated is difficult to determine. Laboratory modelling of complex melts such as those found in slags has not been performed: data is available for ternary oxide systems only, and of the major elements found in tin slag, only the phase diagram for the FeO-Al_2O_3-SiO_2 system has been published (Levin et al 1964 p241). This gives minimum melting temperatures in the range of 1600-1700°C for the slag samples investigated herein, a figure that is clearly very high even in comparison to the temperatures in use in modern reverberatory smelters, which

typically operate at 1200°C. The issue of slag melting points and viscosity generally has been discussed by Bachmann (1980), Kresten (1986) and Freestone (1988).

The experimental data presented in Section 3.1.5 show that archaeological slags begin to melt c.1000°C and do not achieve any real fluidity until temperatures reach c.1100°C. A possible range of working temperatures between 1000 and 1200°C is therefore postulated, with the probability that blowing houses required at least 1100°C.

This experiment also suggested that samples with different microstructures behave very differently at any given temperature. It was observed that glassy slag begins melting at temperatures at least 50°C lower than slag containing crystalline phases, but remains highly viscous even at the highest temperatures obtainable by the furnace. Such a viscous slag would be expected to form ropy flow morphologies when it left the furnace and contain a high proportion of tin trapped as prills. By contrast, the crystalline phased sample, while it began melting at a higher temperature, was very fluid over 1100°C. Slag of this type would tend to form slabs rather than rod-like pieces. With a higher melting point slag even a relatively small drop in temperature could cause it to freeze, both trapping prills (with the concomitant loss of metal), and potentially clogging the furnace. Low viscosity could also potentially be a problem as slag would flow very rapidly out of the furnace, possibly before reduction was complete, if the temperature was not carefully controlled. However, it would allow the free passage of metal through it, so the number of observed prills should be reduced.

Analysis of the compositional make-up of slags presented in Section 3.1.4 reveal a broad trend with respect to different microstructures (categorized as glassy,

feather/needle phased, dendritic and crystalline): slags with proportionally higher tin and/or tungsten contents are more likely to be glassy, while slags with higher iron and/or titanium contents tend to be more crystalline in nature. However, experiments on re-melted slags carried out by the author indicate that cooling rate does affect microstructure: rapid cooling of glassy and dendritic slags produced a glassy microstructure, while slow cooling induced feathery phases to form in glassy slags and for larger crystals to form in the dendritic slag.

Both Fe^{2+} and Ti^{4+} are relatively small ions, and thus are more mobile within a melt than massive ions such as Sn^{2+} and are better able to form crystalline arrangements. However, the type of crystal formation appears to be linked to the relative proportions of iron and titanium in a non-linear way. While high titanium content (often but not necessarily in conjunction with FeO) tends to promote feathery phases or dendrites, the majority of the crystalline samples are low TiO_2 slags (the exception being Charlestown sample 4/20), so this element is clearly not key in the formation of non-dendritic crystals. Iron appears to be the essential species in the formation of crystals, and the data (see p281) suggest a minimum FeO to SnO ratio of 0.4 is necessary in order for crystal phases to form.

The non-crystalline phases (i.e. striations) that appear in several high tin glassy slags have been interpreted as ‘flow bands’ as these features are unlikely to occur as a result of ion mobility, rather the reverse: in these highly viscous slags groups of ions deriving from the cassiterite and the impurities associated with it are moved physically by the action of gravity through the furnace (see also p295).

Bringing together the results of physical and chemical analysis, it is possible to see that, with few exceptions, slag samples from all periods exhibit features consistent

with the observation that high iron/titanium slags often have morphologies indicating that the slag was very fluid, have generally more crystalline microstructures, and contain fewer metallic prills as the metal was able to drop through the slag more easily; high viscosity slags tend to have a higher proportion of larger ions, usually tin, but occasionally also tungsten, producing prill-rich glassy slags with ropy or rod-like morphologies.

The precise effect upon viscosity of any particular combination of chemical species in a tin slag would be incredibly difficult to quantify, not only because of the large variety of ions that must be considered, but also because there is a non-linear relationship between the amount of any metal oxide present and its effect upon viscosity. Small quantities of Group I and II oxides can cause the viscosity of molten SiO_2 to drop by up to 4 orders of magnitude, but at higher concentrations the effect is lessened (Paul 1989). This complex behaviour arises because the arrangement of silicon and oxygen ions within the melt and the bonding between them changes depending upon which metal ions are present and in what concentrations. No work appears to have been carried out to study the effects of different ions on the viscosity of tin slags, though Wright (1966 p90) and Turkdogan (1983 p20) both refer to measurements having been obtained for other multi-component oxide melts including copper smelting slags. Studies of alumino-silicate melts show that the addition of titania causes a lowering of viscosity, owing to the fact that when titanium substitutes for silicon the larger titanium ion is bonded less strongly than a silicon ion (Turkdogan 1983 p81).

4.1.1.2: Mineral Inclusions

One factor that is independent of the viscosity of the slag is the quantity of residual gangue mineral inclusions present in a sample. This will mainly be determined by the quality of the ore that was used and how it was processed. However, mineral inclusions may also enter the charge if old furnace linings were recycled back to the furnace (see Section 4.3).

Inclusions were noted in approximately half of the blowing house slags, and these came in a range of sizes. They were also present in early slags, and in reverberatory slags. The following discussions are based on data summarised in Section 3.1.2.

Documentary and archaeological sources point to a gradual shift from the use of alluvial cassiterite to vein ores. There is also a shift from the probable hand crushing of ores with hammers, to crazing, then stamping, through to modern mechanical crushing methods. A comparison of the sizes of inclusions in slags that were smelted from ores processed using different methods is presented in Table 4.1. No attempt has been made to show a difference between dry and wet stamping, as in many cases it is not known which method was used at a site. Another difficulty arises where artefacts found at certain sites indicate the use of both crazing and stamping (e.g. Gobbett, Retallack and Yellowmead). These sites have been treated separately.

The data show that inclusions may be absent (or sufficiently rare to be unobserved during examination of the sample) in slags from all periods. Furthermore, there is no clear change in the maximum size of inclusion observed. (The single unusually large c.3mm inclusion in one of the slag samples from Retallack bucks the trend.) Although millimetre sized inclusions can be present in each category, there is, as

would be expected, a general decrease in the mean maximum size of inclusions as processing methods become more effective.

Table 4.1: A Comparison of the Sizes of Inclusions in Slags Derived from Ores Processed Using Different Methods

Probable Type of Processing	Size Range (μm)	Mean Maximum Size (μm)
Hand Crushed	0-1000	500
Crazing	0-1000	500
Crazing/Stamping	0-3000	1000
Stamping	0-1000	330
Mechanical	0-1000	223

When examining samples for inclusions, it should be borne in mind that because of the high reactivity of acid slags the majority of inclusions are likely to have been absorbed into the slag, and that crystals that do survive may have been reduced in size. There may be some difficulty in distinguishing between an inclusion deriving from inadequately cleaned ore, and areas of partially reacted granite that probably were originally parts of the inner surface of the furnace. This problem is particularly acute where only a handful of pieces of slag are available for examination, as it may be that the reason the slag has been left on site is because it has been chipped out of the furnace and discarded separately from the other slag.

At Crift Farm a very large number of pieces of slag have been examined and there are certainly samples from this site (not analysed in this work) with >1cm diameter honeycomb-textured granitic inclusions that appear to fit with the interpretation that they have incorporated material from the furnace body (Malham 1996). The same is probably true of the millimetre sized quartz grains in the (probable) reverberatory slag from Eylesbarrow (sample 4/06); a conclusion that is supported by the fact that no similar mineral inclusions occur in sample 4/05, which was taken from the same

large block but furthest from the region where the block had been cleaved. Charlestown has several sub-millimetre crystals within the slag, which is unexpected, considering that by the time this works operated (1834 to 1884) improvements in ore processing methods should have meant that it was possible to eradicate large mineral inclusions. It may be, therefore, that the inclusions derive from old furnace lining material that has been recycled.

In addition to the size of inclusions, the relative numbers of inclusions observed may be informative. A change from alluvial to vein sources might be expected to lead to an increase in the amount of gangue mineral present in the ore. But as washing methods improved more of that gangue should have been removed.

There are examples of slags from all periods in which inclusions are not observed. Examination of the early slags reveals very few inclusions. The Caerloggas and Whitten Knowles slags have no more than a single inclusion each. The presumed early slag from Upper Merrivale (2/25) has slightly more. Alluvial ores may be relatively free of gangue, but some alluvial cassiterite pebbles do contain discrete gangue mineral crystals (see Section 3.2). The Crift Farm slags, which probably derived from alluvial ores broken up by hand crushing and crazing, have a few scattered inclusions, and are thus similar to the Upper Merrivale sample.

Regarding sites with both crazing stones and stamps, inclusions are rare or absent in the slags from Yellowmead and Retallack. The Gobbett slag has a few inclusions. These may derive from mined ore, as Gobbett blowing house is close to the mine of that name.

Inclusions are common in several blowing house slags in the stamped ores category. These tend to occur in slags from blowing houses of relatively late date, or from

houses that on the basis of zirconia content (see p387) were more likely to be using vein ores.

The presence of inclusions in the reverberatory slags has already been discussed (p383).

A comparison of the numbers of inclusions per unit area in slags that were smelted from ores processed using different methods is presented in Table 4.2. A precise determination of the numbers of inclusions was difficult: samples were not of uniform size and inclusions were rarely distributed evenly across a sample; some inclusions were composed of multiple mineral grains; and some inclusions were associated with vesicles, which allowed inclusions from deeper within the slag to be revealed.

Table 4.2: A Comparison of the Numbers of Inclusions in Slags Derived from Ores Processed Using Different Methods

Probable Type of Processing	Inclusions Observed	Mean Number of Inclusions (approximate)
Hand Crushed	0-Few	1.4
Crazing	0-Few	4.0
Crazing/Stamping	0-Common	2.4
Stamping	0-Common	2.1
Mechanical	0-Common	1.7

Note: Few = 3-6 Common = 8+

These rough and ready results do appear to support the theory that increasing use of vein ore caused larger numbers of inclusions to be present in the resulting slags, but that a larger proportion were removed as processing methods became more sophisticated.

The types of minerals occurring as inclusions in slag will be dependent upon the rock in which the cassiterite veins occurred, and any accessory minerals accompanying the cassiterite in those veins. The majority of the tin streams and mines were associated with granite bodies, thus the minerals quartz, feldspar and mica would be expected. Dines (1969) gives information regarding the major accessory minerals found in the veins at various mines. From this study it appears that quartz was present in almost all veins, as well as making up the fabric of the granite itself, while tourmaline and chlorite, though less common, were also recorded at many mines.

Most of the Dartmoor granite is classified as Type B, which is coarse biotite granite (though the actual tin mineralization tends to be associated with muscovite mica rather than biotite) (Alderton 1993). However, there are four small inliers of Type C granite, also biotite-rich but with a fine grain, located within an area north of Brent Moor, south of Ryder's Hill and roughly bounded to east and west by the Rivers Avon and Erme. It might be expected that slag smelted from ores derived from mines in Type C granites would contain smaller mineral inclusions. In fact the only blowing house in this area is Avon Dam, and it is impossible to say whether the ore processed at this site came from one of the Type C inliers. However, the slag from this site contains inclusions that are no smaller than those in some other sites that are situated on Type B Dartmoor granite, so either the ore came from an area where Type B granite dominated, or the stamping of ores at Dartmoor mills is sufficiently good to mask any geological differences. The question must remain open.

Analysis of the composition of inclusions showed that although the majority of the inclusions appear, unsurprisingly, to be quartz, other minerals such as zirconia,

alkali feldspars and possibly mica are also present, and as might be expected more than one type of inclusion can occur in a single piece of slag.

The slag from Yellowmead contains an example of a possible residual mica crystal (although the sodium content of the crystal is rather high for muscovite, even taking into account that the mica group has a relatively variable composition).

Type B and C granites are richer in orthoclase (i.e. potassium feldspar) than plagioclase (i.e. solid solutions of sodium and calcium feldspar), and the compositions of the few slag samples containing what appear to be residual feldspar crystals reflect this. The inclusions in these slags have compositions consistent with their being alkali feldspars (i.e. solid solutions of potassium and sodium feldspars). Feldspar is recorded by Dines (1969 p704-12) as a major accessory mineral in veins in mines about Mary Tavy, which is quite close to the location of the Wapsworthy slag find. It is not recorded in the vicinity of Gobbett or Drakeford Bridge, the two other sites which had slag in which fragments of this mineral occurs.

Inclusions of zirconia were noted in samples from Upper Merrivale, Riddon, Taw River, Teignhead Farm and South Hill. Scrivener of the Institute of Geological Sciences, Exeter, is reported to be of the opinion that elevated levels of zirconia would be indicative of the use of wall rock, i.e. vein ores (Greeves 1981a). On these grounds, out of the samples analysed by Greeves, Upper Merrivale and South Hill were identified by him as being sites where vein ores were probably used. Examples of vein ore have since been found at Upper Merrivale (see section 3.2), and the site is believed to have worked to a relatively late date compared to other blowing houses on Dartmoor (Greeves 1993b, 1994). Of the other sites with zirconia inclusions South Hill is thought to date to the 16th –17th Centuries and documentary

records indicate Taw River was working in 1535, so both these date from a period when vein ores were increasingly being used. Teignhead Farm is probably of the same period. Riddon, however, is thought to be Mediaeval and while the use of vein ores is not unknown from this period, alluvial deposits were a more common source of tin ores.

The presence of relic crystals does not provide unequivocal information relating to the operating temperature of the furnace: firstly, because gangue minerals react with the acid slag, rather than just being physically mixed into it after melting; secondly, because the melting point of minerals of variable composition (e.g. feldspars and micas) is spread over a range of temperatures depending upon the composition (see Section 4.3); and thirdly, because where a mixture of minerals are present, fluxing may occur, lowering the melting temperature of the melt as a whole.

4.1.2: The Effect of Slag Chemistry on Tin Smelting

The interplay between the different elements present in a slag is complex, and the outcome of changing composition is sometimes counterintuitive. Using the chemical analysis of the slags as a starting point, issues relating to key elements will be discussed and the ramifications for smelting considered.

4.1.2.1: Losses of Tin Oxide to the Slag

One question raised by the slag analysis is why did the smelters accept so great a loss of metal to the slag: many blowing house slags contain 10-20% SnO by weight, and a few contain an even greater proportion, while the early smelting slags have concentrations as high as c.45%.

The answer lies in the fact that tin ores, no matter how well processed, contain some gangue minerals. It is the role of slag to separate these impurities from the tin during smelting. However, because tin has a high affinity for silica some tin combines with it to form tin silicate ($SnSiO_3$): the concentration of tin in what has become an acid slag thus theoretically increases with increasing concentration of SiO_2. (Note this is not reflected in the slag analyses given in Table 3.2 as tin can be removed by other processes.) Moreover, the amphoteric nature of tin means that it is not a simple matter to drive tin out of a slag by using a flux such as lime or iron oxide because it is simply absorbed as a stannate (Ca_2SnO_3, Fe_2SnO_3) instead once the slag becomes basic in nature.

There are two possible ways to increase the yield of tin: firstly, to make the conditions in the furnace more strongly reducing in the first instance, and secondly, to return the slags from an initial mildly reducing smelting process to the furnace and re-melt them at a higher temperature. However, efforts to remove more tin from the slag by either method can also cause other metallic elements to be co-smelted with the tin, reducing the purity of the metal produced, which is obviously undesirable.

Considering the compositional data for the early slags, it seems that no attempt at further processing was made. It was perhaps considered uneconomical in terms of time and fuel to attempt to re-melt slags and then obtain tin of lower quality. There is also the possibility that the amount of entrained tin recovered by such a process was not deemed sufficiently great to warrant the time or expense required. When using ores of high purity (up to 79% Sn), the quantity of slag produced in a blast furnace is actually quite low, and so while the proportion of tin in that slag is very

high, the overall losses in relation to the amount of ore entering the furnace are relatively small.

A very rough calculation to estimate the mass of tin lost to the slag that would occur during the smelting of 1kg of an ore concentrate containing 65% elemental tin demonstrates the point (contributions to the mass from the fuel ash are not included):

Mass of Sn in concentrate = 65% of 1kg = 650g

Taking the relative atomic mass of tin as 119 and oxygen as 16, the mass of cassiterite (SnO_2) in the ore can be calculated:

Mass of SnO_2 = (mass of tin x RMM SnO_2)/RAM Sn = (650 x 151)/119 = 825g

The remainder of the ore, 175g, is composed of gangue minerals, which are available to form a slag.

Assume the slag has a composition of 60% gangue and 40% SnO.

If 175g gangue = 60% of the slag mass, 100% of the slag mass = 292g.

Thus the mass of SnO in the slag = 292g – 175g = 117g

So, the mass of Sn in slag = (mass of slag x RMM SnO)/RAM Sn = (117 x 119)/125 = 111g

The mass of tin that can be recovered is the total tin present in the concentrate minus the tin trapped in the slag

Mass of tin recovered = 650g - 111g = 539g

The yield of tin metal from the total mass of the 65% concentrate is therefore approximately 54%, even accepting losses of 40% to the slag.

This can be compared to a slag in which only 10% SnO is present:

If 175g gangue = 90% of the slag mass, 100% of the slag mass = 194g.

Thus the mass of SnO in the slag = 194g – 175g = 19g

So, the mass of Sn in slag = (mass of slag x RMM SnO)/RAM Sn = (19 x 119)/125 = 18g

Mass of tin recovered = 650g - 18g = 632g

A yield of 63% is now achieved.

However, in reality the tin from a smelt producing a 10% SnO slag was likely to be less pure than the metal from the smelt with a loss of 40% SnO. For further discussion of this point see Section 4.1.2.2.

The very careful treatment of the ores described in historical documents suggests that the tinners had some awareness that the best way to obtain a good yield was to smelt ores that were thoroughly cleaned. However, there are limits to how clean an ore can be made, as freeing very small amounts of gangue minerals requires fine grinding. The problems with producing an ore with too fine a grain size are threefold: firstly, as the grain size decreases, more of the cassiterite is washed away during hydraulic separation; secondly, fine cassiterite is more easily blown out of the furnace; and thirdly, as Wright (1966 p76-7) describes, the rate of diffusion of the reductant gas CO into a cassiterite grain (and hence the rate of reaction) is

limited by the fact that the thermal conductivity of the ore particles decreases as their size decreases.

4.1.2.2: The Effect of Iron

Examination of an Ellingham diagram (Figure 4.1) shows that the free energy line for tin lies high in the diagram compared to other metals so in theory it should be a relatively simple matter to reduce this metal from its oxide. The line crosses that of carbon at c.600°C, giving a theoretical minimum temperature at which reduction by carbon should take place, but even performed in a laboratory with pure reagents this reaction requires temperatures in excess of 800°C (Mantell 1949 p149), and a much higher temperature still is necessary for smelting tin ores. The reasons for this are twofold. Firstly, there is a need to attain a reasonable rate of reaction for the reduction of tin oxide. Secondly, when dealing with real concentrates, impurities are present that must be removed as slag if a large proportion of the tin is not to be left unreduced amongst the gangue, and it then becomes necessary to keep the slag in a liquid state, which requires that the actual working temperature inside the furnace is raised to 1100°C or more.

Figure 4.1: Ellingham Diagram for Standard Reactions of Carbon and Selected Metallic Elements with Oxygen (Adapted from Cottrell 1995 p82)

Key:

Antimony	$4Sb + 3O_2 \rightarrow 2Sb_2O_3$	— ····· — ·····
Carbon	$2C + O_2 \rightarrow 2CO$	▲ ▲ ▲ ▲
	$C + O_2 \rightarrow CO_2$	————
Copper	$4Cu + O_2 \rightarrow 2Cu_2O$	— — — —
Iron	$2Fe + O_2 \rightarrow 2FeO_2$	~ · ~ · ~ · ~ ·
Molybdenum	$Mo + O_2 \rightarrow MoO_2$	· · · ∧ · · · ∧ · · ·
Tin	$Sn + O_2 \rightarrow SnO_2$	·—·—·—·
Titanium	$Ti + O_2 \rightarrow TiO_2$	·····
Tungsten	$W + O_2 \rightarrow WO_2$	— ·· — ·· — ··

Note: Data for arsenic oxide is not available; this element is usually occurs as the sulphide

Interpreting the Ellingham diagram:

The lines on the diagram indicate the stability of an oxide as a function of temperature. Toward the bottom of the diagram metal oxides become harder to reduce. The line for the reaction $2C + O_2 \Rightarrow 2CO$ *cuts across the lines for many metals. When the carbon oxidation line goes below a metal oxidation line carbon can reduce that metal oxide to metal.*

The scale labelled 'Po_2*' indicates the partial pressure of oxygen that is in equilibrium with the metal and metal oxide at a given temperature. If the oxygen partial pressure in the furnace is lower than the equilibrium value then the oxide will be reduced. To determine equilibrium* Po_2 *for a particular reaction at a given temperature, find the point on the reaction line corresponding to the temperature of interest. Draw a straight line from the point 'O' on the left hand side of the diagram, through the point on the reaction line, to the* Po_2 *scale.*

When carbon is used as a reducing agent, a minimum ratio of CO to CO_2 *is necessary: less easily reduced metal oxides require a higher proportion of CO. Determine* CO/CO_2 *ratios as for partial pressures, but use the point 'C' on the left hand side of the diagram and the '*CO/CO_2*' scale.*

The problem with working at these elevated temperatures is that, as the Ellingham diagram shows, the activity of iron oxide in this temperature range is very similar to that of tin oxide (CO/CO_2 for Sn = 0.0-1.0 at 1100°C (estimated) cf. Fe = 0.0-1.0). Iron can therefore be co-reduced with the tin, resulting in the formation of the tin-

iron alloy hardhead. As conditions within the furnace become increasingly more reducing, the proportion of iron entering the tin increases. This effect has been directly observed: in 1868, when hand-blown furnaces in Banca were replaced with blast furnaces using mechanised bellows, the quality of the tin obtained deteriorated, despite their using the same concentrates, because the new furnaces operated at a higher temperature and the atmosphere was more reducing, which caused iron to be co-smelted with the tin (Thibault 1908 p164). The advantage of the new furnace was that it produced a greater yield of tin from the same amount of concentrate.

This phenomenon follows from the tin-iron equilibrium that is set up during smelting. Tin and iron divide between the slag and the metal at equilibrium, according to the equation

$$\frac{\text{Sn in metal}}{\text{Fe in metal}} \times \frac{\text{Fe in slag}}{\text{Sn in slag}} = k$$

where k is the equilibrium constant.

Unfortunately, it is not possible to calculate actual tin yields from slag compositions alone; it is necessary to know the chemical composition of the ore. To complicate matters further, calculations of the equilibrium constant show that it is actually not a constant: its value is highly flexible and varies in a non-linear manner with the quantity of iron in the metal (Wright 1966 p80-6). Few experimental determinations have been attempted, mostly at much higher temperatures than were probably used in early furnaces, and with conflicting results being obtained. As a result, it is difficult to draw any firm conclusions from the theory of tin-iron equilibrium.

The interaction between tin and iron during smelting can be summarized as follows. Under mildly reducing conditions, tin is produced in preference to iron, but losses of

tin to the slag are high. Strongly reducing conditions promote the formation of hardhead, as iron is co-smelted with the tin, but more tin is removed from the slag, increasing overall tin yield.

The modern Two Stage reverberatory smelting process (Parker et al 1990; Smith 1996) takes advantage of this phenomenon. The first smelt is carried out under gently reducing conditions producing tin of high purity and a slag with a high tin content. The high tin slag from the first smelting is returned to the furnace and a second smelt is then undertaken using more strongly reducing conditions, producing hardhead and a slag from which almost all of the tin has been removed. Further processing of the hardhead is then carried out.

The documentary evidence for blowing houses appears to indicate that a similar two-stage process was used (Cotton 1664; Anon 1670), with slags being re-smelted separately from ores. The blowing house slags analysed in this work may therefore have been through the furnace more than once.

Given that increasing iron content appears to increase tin yields, it is useful to consider the other consequences of using lower grade ores in which iron oxide is present in greater quantities.

Increasing the amount of iron present in the charge means that more iron silicate can be formed, and if silica is tied up as iron silicate, this reduces the opportunity for tin silicate, which is the main cause of tin becoming trapped in the slag, to form. A higher yield of tin is therefore obtained, so increased iron is, in this respect, beneficial. However, any iron oxides not entrained as silicate are available for co-reduction with the tin, and the metal purity is reduced as alloying occurs. This can be problematic as the iron in an iron-rich metal mixture can lock up many times that

mass of tin in refining drosses: tin accounts for 80% of the mass of hardhead occurring in the form $FeSn_2$, which means that if the metal being produced contains just 1% iron, 5% of the total furnace output could be hardhead. There is, therefore, a limit to how much iron can be allowed into the metal before it becomes uneconomical to process (Grant 1994; Smith 1996).

The amount of iron in archaeological slags is very variable, as the analytical results in Table 3.2 show. While all the early slags tend to be low in iron, there does not appear to be any temporal trend within the results obtained from the blowing houses and reverberatory smelters.

Iron Oxides in Blowing House Slags

It is unlikely that the iron oxides were added deliberately to the blowing house furnaces as flux. An examination of FeO and SnO content in Dartmoor blowing house slags shows a general trend of increasing FeO/SnO ratios progressing from the southwestern edge of Dartmoor to the northeast (see Figure 4.2).

Using information from Dines (1969) regarding the mineral output of Dartmoor mines it can be demonstrated that iron oxide contents in slag roughly correspond to changes in local mineralogy: blowing houses with high FeO/SnO ratios tend to be situated in areas where levels of extraction of iron minerals were higher (see Figure 4.3). The levels of iron minerals in the ore in these areas would be higher, and lacking any effective way to clean these ores, be they alluvial or mined vein ores, the blowers would be forced to tailor furnace conditions and refining methods to a high iron charge.

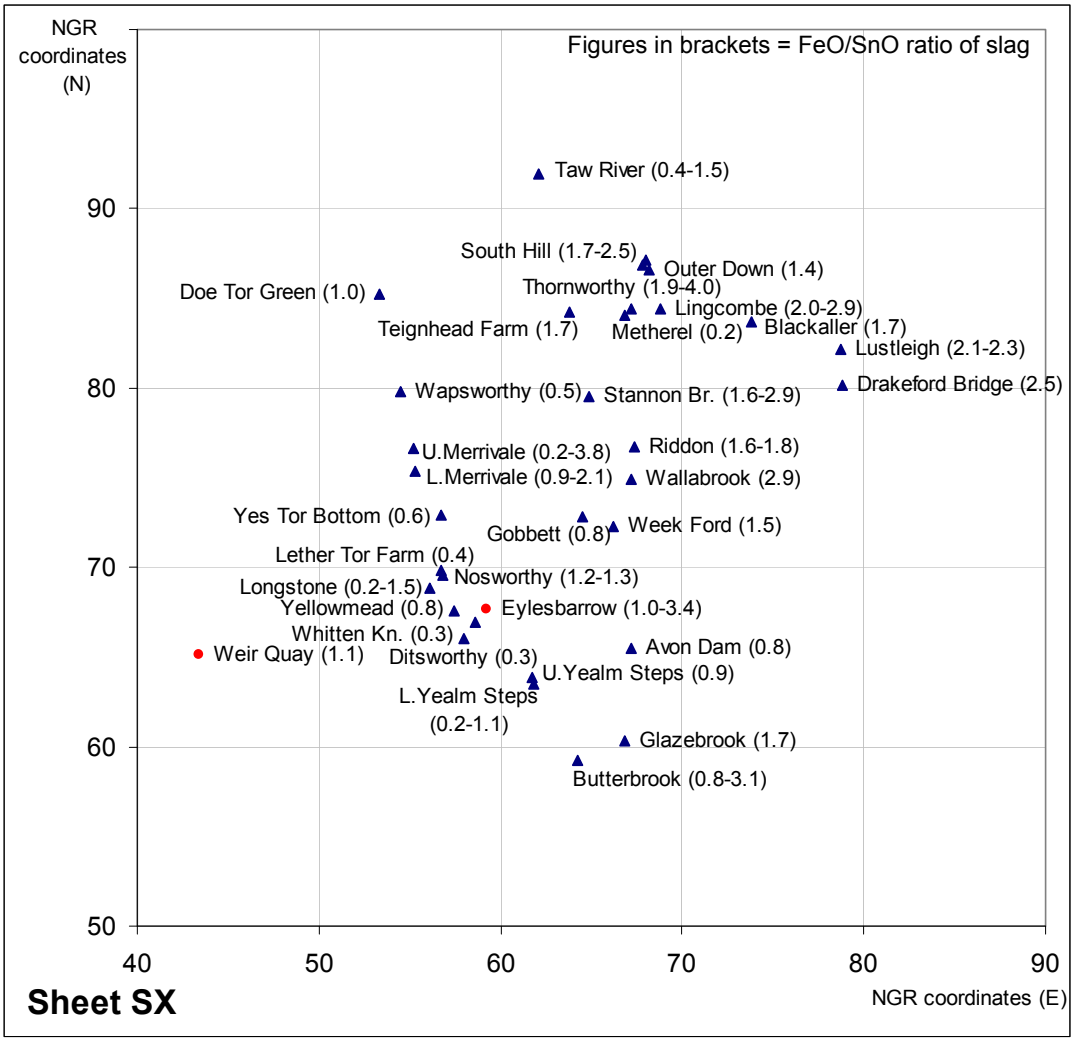
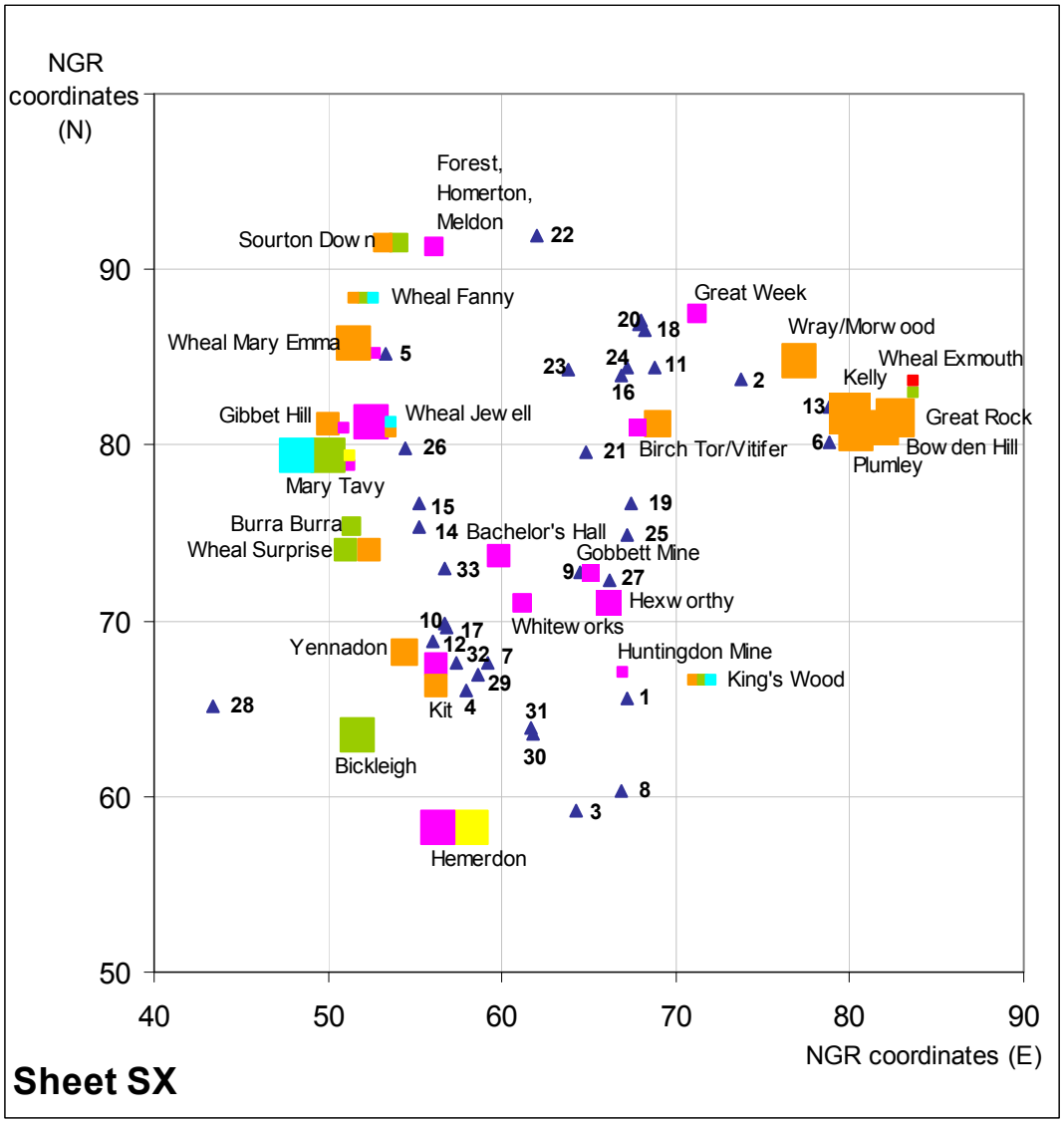


Figure 4.2: Map of Dartmoor Tin Smelting Sites showing change in FeO/SnO ratios of Slags (Blue triangles = pre-reverberatory smelting sites; Red circles = Smelting works with reverberatory furnaces).

Although the dearth of compositional analyses carried out upon Cornish blowing house slags means that a geographical correlation of this kind cannot be shown for any of the granite masses of Cornwall, it can be noted that these slags, with their low iron oxide contents, derive from areas that, according to output figures published by Dines (1969), historically had low levels of iron extraction.

Figure 4.3: Map of Devon showing Output of Metallic Ores from Selected Mines in relation to Tin Smelting Sites



Key to Smelting Sites:

1: Avon Dam. 2: Blackaller. 3: Butterbrook. 4: Ditsworthy. 5: Doe Tor Green.
6: Drakeford Bridge. 7: Eylesbarrow. 8: Glazebrook. 9: Gobbett.
10: Lether Tor Farm. 11: Lingcombe. 12: Longstone. 13: Lustleigh.
14: Lower Merrivale. 15: Upper Merrivale. 16: Metherel. 17: Nosworthy.
18: Outer Down. 19: Riddon. 20: South Hill. 21: Stannon Brook. 22: Taw River.
23: Teignhead Farm. 24: Thornworthy. 25: Wallabrook. 26: Wapsworthy.
27: Week Ford. 28: Weir Quay. 29: Whitten Knowles. 30: Lower Yealm Steps.
31: Upper Yealm Steps. 32: Yellowmead. 33: Yes Tor Bottom.

Key to Mine Output:

Antimony Arsenic Copper Iron Tin Tungsten

Size of square indicates order of magnitude of mineral extraction.

The conclusion to be drawn from these observations is that, as ores were usually not transported very far to blowing houses – and under Stannary Law were certainly not taken out of the district in which they were mined, local geology had a strong influence upon the smelting process, to the point where it may actually mask changes in slag behaviour that occurred as a consequence of technological developments (hence the occurrence, at some sites, of pieces of matt slag that bear a resemblance to reverberatory slags).

Iron Oxides in Early and Reverberatory Smelting Slags

Given the range of chemical compositions and morphological types exhibited by blowing house slags as a result of geological factors, which can be so great as to make it difficult to distinguish between slags produced by earlier and later technologies, it is useful to make a comparison between blowing house slags and samples from different periods.

As has been noted previously, the iron content of all early slag samples is relatively low. The Bronze Age slag from Caerloggas and the Early Mediaeval pre-blowing house slag from Crift Farm follow the same trend as other Cornish slags, i.e. low iron oxide concentrations accompanying high levels of tin oxide. There is no real difference between the amounts of these two chemical species in the Crift Farm slag and the amounts seen in the blowing house slag from Hurdon. The levels of tin oxide in the Caerloggas slag are considerably higher than in blowing house slags, however. Turning to Dartmoor, the possible early slag from Upper Merrivale (sample 2/25) has a low iron oxide content (though not unusually so: some slags from the blowing house at Upper Merrivale do have similarly low levels), but the tin oxide content of this slag is very high, and taken overall, its composition is

comparable to the Caerloggas slag. Whitten Knowles (sample 2/36) has a marginally higher iron oxide content than other early slags, but that is nevertheless on a par with levels seen in blowing house slags from that part of Dartmoor. Unlike the blowing house slags, the tin oxide content of the Whitten Knowles slag is quite high (c.33%), but in keeping with the predictions of the tin-iron equilibrium, is lower (by c.10%) than other early slags.

The mildly reducing smelting conditions implied by the very high tin oxide contents of the early slags would preclude the co-smelting of any iron oxides present, with the result that highly pure metal was produced. The tin-iron equilibrium would also promote the formation of good quality tin metal. An examination of the prills from the early slags shows that the prills are indeed relatively free from iron.

When attempting to compare blowing house and reverberatory slags, the first problem encountered is that there are a number of sites where, according to documentary sources, both blast furnaces and reverberatory furnaces worked simultaneously (Carvedras (Barton 1971 p82) and Eylesbarrow (Cook et al 1974) works fall into this category), or where one type of furnace was replaced by another on the same site (the smelting works at Trereife is believed to have been erected on or close to the site of the old Trereife blowing house (Brooke 1998 p216)). The identification of slags from these sites as reverberatory smelting slags is not, therefore, 100% certain. This is not the case for Weir Quay and Charlestown (although there were blowing houses working in St Austell at the same time as Charlestown smelting works, which had only reverberatory furnaces, the operations were entirely separate and situated some distance apart (Barton 1967 p63, p128)), so

it is fairly safe to assume that samples from these two sites were produced by the later technology.

The second problem is that, as descriptions of reverberatory smelting practice make quite clear (see p175), different types of compositionally distinct slag were produced during the course of a smelt. Reverberatory furnaces smelting ore were kept closed (except for occasional rabbling) until the whole charge was molten, and as no tapping was carried out, a layer of slag accumulated over the tin on the hearth and settling by gravity could occur. This slag was known as 'pulled slag' as it had to be removed manually from the furnace using rakes or rabbles once smelting was complete.

There was also a fluid slag known as 'glass', which ran out of the furnace into the float with the metal when the furnace was tapped.

Finally, there were slags that had been re-smelted, passing through the furnace for a second time, separate from the ore.

The majority of pre-20th Century archaeological reverberatory slag samples are likely to be 'waste' slags. There are two basic sources of waste slag: firstly, the slags that have been put through the furnace a second time and re-smelted, and secondly, 'top pulled' slag, which comprises the upper third to three quarters of the viscous slag (or scoria) layer formed inside the furnace. In the 18th and early 19th Centuries this type of slag appears to have been routinely discarded without further reprocessing, as it was considered 'clean' (Smith 1996). Top slag would have contained very little tin in the form of prills, the dense metal having been encouraged to drop through the slag, but could still have had a relatively high proportion of tin oxide within it.

Optical microscopy shows that prills are either absent, or rare and of very small size, in all of the reverberatory slag samples analysed.

It is also possible that the type of slag known as 'glass' slag could be found in the archaeological record. Glass slag was the very fluid slag that flowed out of the furnace with the tin metal. Its glassiness possibly resulted from the resultant rapid cooling rate. Whether this glass slag was returned to the furnace after being taken off the surface of the metal, or was discarded, appears to have depended upon an individual smelter's judgment (see Section 4.1.3).

It is less likely, though not impossible, that samples recovered from reverberatory sites would fall into the categories of middle or bottom pulled slags. Middle slags were prill rich and were crushed. Bottom slags generally had large proportions of tin metal within them and were habitually returned to the furnaces. Examples of these types of slag might be found if, for instance, work at a site ceased before the slags could be retreated.

In modern reverberatory furnaces using the Two Stage process (Mantell 1949 p144, Smith 1996 p97 and Parker et al 1990) slag from primary smelting usually contains between 10 and 20% tin with a similar proportion of iron. Secondary stage smelting produces slag with a greatly reduced tin oxide content: as little as 1% can be achieved, or even lower if a lime flux is utilized; iron content is again 10-20%.

The reverberatory smelting sites that have yielded slag for analysis in this work pre-date the Two-Stage smelting process (all but Eylesbarrow (1822-31) closing in the last two decades of the 19th Century) and unfortunately accurate compositional analyses are not available for different types of slag from furnaces that operated in this earlier period, although it was said that waste slag contained 2 to 5% tin metal

(Smith 1996). Lacking this information, to assign the archaeological reverberatory slag samples to a particular category on the basis of composition is fraught with difficulty.

A summary of contemporary descriptions of reverberatory slags is given in Table 4.3.

The number of reverberatory slag samples that have been analysed is very small, so it is difficult to make concrete statements regarding iron oxide contents, but there seems to be no particular difference in iron oxide content between samples from Devon and Cornwall. The lack of any geographical correlation similar to that seen for the blowing houses is not really surprising in view of the fact that ores were brought to large smelting works from many different mines within a wide geographical area, and indeed from the mid 1800s were sometimes imported from abroad. For example the smelter at Charlestown dealt with ores from Bolivia (which are typically richer in tin), Peru and Australia, as well as from the St Agnes area and the Tamar Valley (Barton 1967 p129; Charlestown Shipwreck & Heritage Centre 2006). In addition, it was common practice to return iron-rich smelting drosses to the furnace along with fresh ore concentrates.

When considering blowing house slags, it was observed that higher iron oxide contents in slags tend to be associated with lower tin oxide contents, however the same trends cannot be seen in the compositional data from the reverberatory slags. Not only is the data set rather too small to reveal any overall trends, but also the removal of portions of the slag after the initial smelting, while other parts of it were recycled back into the furnace along with impure metal and fresh ore, could have caused many differences in composition.

Table 4.3: Types of Slag formed in Reverberatory Furnaces

Source	Date	Types	Slag type	Slag type	Slag type	Slag type	Notes
Kalmeter (Brooke 1998 p346)	1724	2	Slag from slag re-smelting: None runs out of the furnace. Raked out through the door; it is not smelted any more but is stamped small.			Slag from ore smelting runs out with molten metal when smelting complete. Skimmed off and smelted again.	Separate smelting of ore and slag
Pryce (1778 p283)	1778	2	Slag that forms a cake in the bottom of the furnace and is stamped to remove prills.			Small amount of slag that (sometimes) flows out with metal.	
Dufrénoy (1837)	1834	3	A: the final rejected slag, poor in tin and amounting to c. ¾ of the total	B: slag containing small prills of tin amounting to only 5% of the total which was stamped,	C: a slag not greater than 10% in volume containing much metal that was recycled.		300 kg ore gives 60 kg slag
Louis 1911 p96 on Penzance Works (also Thibault 1908 p188; Mantell 1949 p130)	Early 20th Century	4	Pulled slag: Top layer of pulled slag drawn out through the working-door, by means of rakes or rabbles; constitutes about $^2/_3$ of the whole; is considered clean enough to be discarded.	Pulled slag: Next layer contains a good deal of tin in the form of shot or prill; sent to the stamps to be crushed and washed.	Pulled slag: Remainder requires re-smelting together with the prill obtained by the treatment of the previous lot.	Glass: Molten slag remaining on surface of the metallic tin and tapped out with it. Separates out in float and removed when solidified. Re-smelted later.	Waste slag contained 2-5% Sn

At the relatively high temperatures employed in reverberatory furnaces co-smelting of iron would be expected, leading to the formation of hardhead. Analysis shows that prills containing a mixture of iron and tin actually only occur in the slags from Trereife, and the prills in Trereife sample 2/35 also contain arsenic, while sample 2/36, originally part of the same large block as 2/35, appears only to contain prills of tin, which is possibly an artefact of gravitational separation of metals of different densities. None of the prills in the Charlestown slag were big enough to analyse, but their irregular shape implies that they are probably not pure tin (see p308), and the high iron oxide content of the Charlestown slag suggests that iron is a likely candidate for one of the alloying metals.

Metal Quality in Prills

In relation to the iron content of metallic prills trapped within the slag, the results of the compositional analysis fail to reveal any trends with respect to production technology. On the grounds that prills are almost always the only tangible source of information available regarding metal quality, before attempting to draw any conclusions about smelting conditions based upon the slag and prill analysis, it is pertinent to consider the extent to which the composition of metallic prills reflects the purity of the tin being produced. The simple answer to this is: it does not.

There are many difficulties associated with equating the two. For one thing, it is known that the composition of the metal leaving the furnace changes during the course of the smelt. In part this is due to easily reducible metals such as copper, arsenic and antimony coming out of the ore in the early stages of smelting (Wright 1966 p84). Differences also occur because some tin oxide can be reduced to metal below the temperature at which the slag melts, as CO gas diffuses through the charge, and this tends not to be

contaminated with iron as may be the case later in the process. This tin has a very low viscosity and so will flow out of the furnace very quickly. By contrast, the tin produced later forms through reduction of cassiterite within the slag; oxygen transport being effected through interactions of the slag, cassiterite and any iron present, which is also likely to be reduced (Wright 1966 p76). The tin trapped in the slag as prills will almost certainly have been produced through this latter mechanism.

In 1586 the earliest reference to 'pillion tin' - when ingots were formed by re-melting prills mechanically recovered from slag - makes it clear that this tin was treated as a separate grade of metal, and it was stamped with a letter P (Beare 1586 p32), implying that it was not necessarily of the same quality as the furnace tin.

It is also necessary to take into account the fact that some recycling of slags has probably occurred. As discussed below (Section 4.1.3), there is a difference in the quality of metal from an ore smelt and from a subsequent re-smelt of the slag. There is no way to determine whether a piece of slag is the product of the first smelting process (either being from a site where recycling was not carried out or becoming lost before mechanical crushing could take place to recover the prills in it), or if it has been discarded after being recycled back to the furnace one or more times. In the latter case, the prills can provide information only on the quality of 'sinder tin', not the bulk of the metal produced at the site in question.

Another difficulty is that a single prill is not necessarily even representative of all the metal trapped in the slag. The number of prill analyses carried out on archaeological samples is only very small, but even so it can be seen that where more than one prill was analysed in a single piece of slag, quite often those prills had markedly different

compositions. To base any assumption upon the composition of a single prill is therefore potentially erroneous.

On a more promising note, chemical analysis of the products of experimental smelts performed by Earl (1986) showed only small differences between the ingot metal and trapped prills.

Provided the data is treated with caution, therefore, its use in the following discussion is not wholly without foundation.

Too few analyses of Cornish slags have been carried out to draw any firm conclusions from the data, but it is possible to remark upon the fact that all known Cornish blowing house slags have low to medium iron oxide contents. The highest is that of the Trevellas Porth slag with 17.3%, and as expected this slag has a slightly lower tin oxide content (15.6%) than the slags from Hurdon and Retallack. When the prills in the slag from these sites are examined, it can be seen that all are relatively pure tin.

The Dartmoor blowing houses, which are relatively well represented in the data, exhibit a much wider spread of values for both tin and iron oxides. SnO contents range from c.5% to over 35%, while FeO contents range from as low as c.6% up to more than 30%. Iron oxide acts to reduce levels of tin oxide trapped in the slag: generally, for iron oxide contents below c.10%, tin oxide>iron oxide, while for iron oxide contents over c.15% tin oxide<iron oxide.

An examination of the composition of the prills in Dartmoor blowing house slags shows two things. Firstly, that slag samples with higher iron oxide contents tend to contain no metallic prills, or prills of extremely small size. As the study of microstructures suggests that high iron slags have relatively low viscosities, allowing

free movement of metal through the slag, a minimal amount of metal trapped as prills would be expected, this is provided that a sufficiently high working temperature could be maintained to prevent the slag freezing.

As it is not possible to analyse the chemical composition of the very smallest prills, the purity of the metal cannot be commented upon. However, the theory of tin-iron equilibrium would predict that they contain some iron in addition to tin.

For those slags with prills large enough to permit analysis, it is often but not always the case that high iron oxide slags contain prills that are contaminated with some iron, while low iron oxide slags tend to contain pure tin prills or have prills with iron at concentrations of <1%. Again, this is roughly consistent with the predictions of the tin-iron equilibrium.

While bearing in mind the problems associated with equating the composition of metallic prills with the composition of the bulk metal leaving the furnace, from the above results it may be suggested that the metal being produced in those furnaces that also generated a high iron slag would have contained some hardhead, which would have necessitated further refining to produce clean metal.

Prills within slags from early sites, regardless of their location, are composed of tin that is relatively free of impurities. This is consistent with their being smelted with low blast pressures from manually operated bellows, which generates mildly reducing conditions.

Only one smelting house slag, which is probably a reverberatory slag, has prills that are pure tin: this is Eylesbarrow, which to a large extent smelted ores from its own mine that were considered to be of exceptionally good quality (Cook et al 1974).

4.1.2.3: The Effect of Other Metallic Elements in Slags and Prills

Calcium (Lime)

Although lime is a useful flux in other metallurgical processes, its use in tin smelting can be problematic. It has already been noted that the effect of adding bases to a silicate slag is to cause tin to act as an acid and form stannates. In this case, as SnO from the reduction of cassiterite comes into contact with calcined limestone, calcium stannate is formed, which effectively locks tin into the slag. In addition, the formation of tin metal in the early stages of smelting is curtailed with the result that overall iron content of the metal may be increased (Parker et al 1990). The melting point of the slag is also raised, with implications for fuel consumption, difficulties associated with the stronger reducing conditions that appertain to higher temperature working, and also the increased likelihood of furnaces becoming clogged owing to slags freezing at higher temperatures. A very fluid slag would also tend to have a short residence time in a shaft furnace, which could result in partially reduced ore being carried out of the furnace.

The advantages of using lime as a flux is that it considerably lowers the viscosity of a slag. Tin metal can flow more freely through a fluid slag, reducing the amount of tin trapped prills, and the slag flows more easily out of the furnace (provided that freezing can be avoided).

Analyses of blowing house slags, and those from earlier periods, which all have CaO contents between 0.3 and 4.3% (see Table 3.2), indicate that lime was not a deliberate addition to the charge. It must therefore be assumed that the blowers considered that the advantages of using lime as a flux were outweighed by the disadvantages, and that the performance of their furnaces was satisfactory with slag fluidities determined solely by the presence of naturally occurring iron oxides.

The most likely source for the small amount of CaO in all these slags is the fuel. Analyses of oak wood ash by Sanderson and Hunter (1981) and Thomas (2000 p71) indicate that calcium is the most abundant element in fuel ash, accounting for approximately 15% of its non-carbon mass, although different vegetable-based fuel sources (e.g. peat or charcoal from different tree species) contain varying quantities of calcium. Earl (1991) speculated that the blowers' habit of using different fuels for ore smelting and slag re-melting could, in part, have developed as a result of the observed changes in slag fluidity caused by the unintentional addition of more or less CaO.

The compositional analyses show that the later Cornish blowing house slags have CaO contents 1-2% higher than the Devon blowing house slags. If it is accepted that the slightly higher CaO content in the Cornish blowing house slags results from an increase in the amount of fuel ash entering the slag, one possible means by which this could occur is by slag being recycled back to the furnace. The results would therefore appear to suggest that recycling of slags was carried out in Cornish blowing houses more often than was the habit in Cornwall in earlier times (cf. the low CaO content of Crift Farm slag) or in the Devon blowing houses. While it cannot be assumed that modern reconstructions of shaft furnaces provide a true picture of furnace operating conditions in the past, experimental smelting carried out by Earl does lend support to this interpretation in that it showed that an increase in lime content occurred when slags were re-smelted (Earl 1986; Tylecote et al 1989).

Before the 20th Century the use of lime in reverberatory furnaces also appears to have been limited, CaO contents falling in the range 0.4 - 2.8%. Worth (1940) suggested that the crystalline appearance of a sample of slag from Eylesbarrow that he examined was a consequence of a lime flux having been used, but this assertion is not supported by

chemical analysis carried out on samples from Eylesbarrow, presented in Greeves (1981) and in this work.

In his description of early reverberatory practice, Pryce (1778) made no mention of fluxes being added to the charge.

By contrast to the results presented in Table 3.2, the reverberatory slag from Angarrack analysed by Tylecote et al (1989) had a CaO content of 11.47%, while some 20th Century slags have CaO contents of up to 28% (Bray 1947 p445; Wright 1966 p89). Thibault (1908 p188) refers to the addition of small amounts of slaked lime to reverberatory furnace charges at the beginning of the 20th Century, and descriptions of later Cornish reverberatory practice (e.g. Mantell 1949 p130) include references to the use of limestone as a flux, so this appears to have become standard practice by the end of the 19th Century.

Titanium

Titanium is not reduced by carbon, so does not form troublesome alloys with tin, but its presence in slag can be a problem: Wright (1966 p105) states that at concentrations over 5%, high melting point compounds can precipitate out of the slag, and this could clog the smelting hearth. The distribution of sites with relatively high TiO_2 contents was discussed in Section 3.1.4.1 (p269-70). High titanium contents are a common feature of the slags from the northeastern parts of Dartmoor, and thus may have caused some difficulties for the smelters working in this area.

Copper, Arsenic and Antimony

Wright (1966 p84) states that oxides that are more easily reduced than tin and iron, such as copper, arsenic and antimony (see Figure 4.1, p392), will be found in the first

tin out of the furnace. Certainly none of the slag samples analysed contained a bulk copper content of >0.1%. This suggests that tin ores, particularly the alluvial ores used in the blowing houses, did not contain much copper.

Copper is only a rare constituent of metallic prills. When present, it is usually at levels of 0.1-0.3%. A single prill from Retallack contains 2.5%; it also makes up one third of one of the prills in the slag from Trereife. These data suggest that copper is concentrated in the metallic tin, in which it would be soluble (see the Sn-Cu phase diagram in Appendix 12), rather than remaining in the slag. Given the readiness of any small quantities of copper that may have been present in the charge to undergo reduction, this metal would have been produced rapidly so that prills containing it would probably have had time to percolate through the slag and be lost from it.

Arsenic and antimony, both of which are readily soluble in tin, are also relatively rare components in both slag and prills. When alloyed with tin, antimony increases its hardness; arsenic also increases hardness, and even at relatively low concentrations makes the tin brittle. Early smelters would probably have been able to avoid arsenical ores as they often have a distinctive smell, and documentary sources reveal that from at least 1670, ores were treated by roasting (Anon 1670).

The ability of the blowers to keep arsenic to a low level is attested to by the fact that arsenic was either not detected or occurred at only trace levels in any of the slag samples or the prills they contained. Later slags have equally low arsenic contents. At one site only – Trereife – arsenic occurred in three prills, accounting for between one and two thirds of the total metallic content of the prill (contrasting with the low levels in the slag matrix). Dines (1956) notes the mining of arsenic in the St Just area of Cornwall, possibly the source of the ore for Trereife.

The fact that antimony and arsenic both form very stable compounds with iron (Wright 1966 p133), which is also present in the Trereife prills (in two of the three cases already associated with the arsenic), suggests that it would still be possible to produce relatively clean tin. The purification of tin by liquation relies on the fact that iron is only barely soluble in tin at the melting point of tin (232°C) (see Sn-Fe phase diagram in Appendix 12), and though arsenic is still soluble at this temperature, its propensity to form compounds with iron would lead to its being concentrated in the insoluble portion of the mix.

Antimony occurs in the slag samples only at levels below 0.5%, and is present at no more than trace levels in any prill, save one, which suggests that very little antimony was originally present in the ores used. The exception is a prill in the Ditsworthy slag, which, unusually, is wholly composed of antimony. Despite this, levels in the slag itself are low, supporting the assertion that this element is readily reduced out of the ore and preferentially partitions into the metal. The source of the antimony is not clear. Dines (1956) records no antimony extraction on Dartmoor.

Analysis carried out by Tylecote et al (1989) noted antimony in tin prills in slag samples from Retallack and Crift Farm (1.03% and 1.76% respectively), with X-ray mapping indicating higher concentrations than in the surrounding matrix.

Tungsten

Tungsten enters the furnace in ore contaminated with tungsten minerals, which have a similar specific gravity to cassiterite thus precluding their removal during washing, and has a detrimental effect on the smelting process. It was only in the 19th Century that chemical cleaning of tungsten-rich ores was introduced: in 1855 Leifchild (p208) comments that ‘a new process by Mr Oxland easily separates the wolfram from the tin,

and the ore may be thoroughly cleaned by it', but this additional process may not have proved economically viable for the smaller operators. It is reported that the free-selling tributers working in the 1930s around South Wheal Breage (SW6230) would not collect tungstanic ores as the local independent tin dresser would not buy them, being unable to separate the tungsten from the tin (Polglase pers comm. 12/7/03).

Tungsten-rich ores were probably avoided by early tinners once they were identified, but, as tungsten is very commonly associated with tin in small amounts, it would have been very difficult to avoid completely.

Given the number of slag samples that contain this chemical species, it is thus useful to consider the behaviour of tungsten during smelting. One problem is that even at very low concentrations (c.2%) tungsten raises the viscosity of a slag (Wright 1966 p102). Another is that tungsten-rich slags (i.e. >5% by weight) can have high freezing points (Wright 1966 p105), which would lead to furnaces becoming clogged if the temperature dropped. Thibault (1908 p155) notes that the consequence of the slag being 'more infusible' is that it causes 'a greater loss of tin, in the form of metallic globules', i.e. more prills trapped in the slag.

The slag analysis shows that the blowing houses at Hurdon (SX210823), Upper Merrivale (SX55197664), Taw River (SX62059197) and Upper Yealm Steps (SX61726385), may have experienced difficulties with at least some of their slags. The tungsten content of some of the Trereife (SW455294) slag samples was also very high.

Dines (1956 p582-608) reports quantities of tungsten being mined in the area around Hurdon (e.g. North Hill (SX2776), Vincent (SX209795) and Caradon (SX298702) mines) so this element is likely to have been present in relatively high concentrations in ores brought to Hurdon blowing house. Very high levels (c.15%) are present in the slag,

and this probably contributed to the number of fairly large prills that are observed in samples from this site. However, analysis of the metallic prills in the Hurdon slag shows that tungsten is concentrated in the slag only. This is also true for the samples from Upper Merrivale, Taw River and Upper Yealm Steps. The prills are tin of high purity; tungsten accounts for 0.2% by weight of the metal in most of the prills from these sites, the highest concentration being 0.7% in one of the Upper Merrivale samples.

This observation agrees with the findings of Tylecote et al (1989), who used X-ray mapping to show that tungsten was concentrated in the matrix of slag from Retallack (although electron probe microanalysis of the sample failed to detect it). No compositional analysis of the prills in the Retallack slag was published at that time, however data presented in Table 3.10 suggests that the metal would probably have been tin with contaminants at only trace levels.

Examples of tin prills containing tungsten over 1% can be found in low tungsten pre-reverberatory slags from Butterbrook, Crift Farm, Doe Tor Green, Nosworthy and Wallabrook, and in the reverberatory slag from Carvedras.

As with Hurdon, there is the suggestion of a link between ore mineral production and the location of Dartmoor sites that have tungsten in their slags or prills. With the exception of Wallabrook, the Dartmoor sites are distributed roughly around the western and southern edges of the granite. Though there is no data relating to the concentration of tungsten minerals associated with the granite in the immediate area of the smelting sites, tungsten is present in lodes in areas further west in sufficient concentrations to have warranted exploitation in the 19th and 20th Centuries (Dines 1956 p623-712; Harris 1968 p38). Extraction of tungsten minerals is recorded from mines in the killas

around Marytavy (c.SX5178), Plympton (c.SX5556), Gunnislake (c.SX4272) and Hemerdon (c.SX5758), and in the small granite body of Kit Hill (SX3871); all predominantly tin producing areas. This is not to suggest that tin ores from districts situated across the River Tamar in Cornwall were smelted in Dartmoor blowing houses, only that there might be a continuation of the tungsten mineralization eastward into those areas for which mineral production statistics are not available. There is no record of workable tungsten deposits in the vicinity of Crift Farm, or the Redmoor alluvial deposits, from which it is presumed the ore smelted at Crift Farm derived. Potential sources of ore for the reverberatory smelters are more difficult to determine, as ores were brought to the smelter from mines in a wide geographical area.

The presence of tungsten in prills deriving from tin slags requires some explanation: firstly, because the solubility of tungsten in liquid tin is extremely low, so the two do not alloy (Madelung 1998 p1); secondly, because although it is possible to obtain tungsten using carbon as a reducing agent, much higher temperatures and stronger reducing conditions are required than is the case for tin metal (at 1100°C CO/CO_2 for Sn = 0.0-1.0 (estimated) cf. CO/CO_2 for W ≈ 1.0, see Figure 4.1, p392).

Typically, therefore, tungsten will stay in the slag, as the analyses of the Hurdon, Upper Merrivale, Taw River, Upper Yealm Steps and Trereife samples attested. However, if iron is present in the charge, and is being smelted out with the tin to form hardhead, under such conditions tungsten, which is highly siderophilic (i.e. alloys readily with iron), may be carried out of the slag in the hardhead (Wright 1966 p84). Tungsten and iron form 2 stable intermetallic compounds, FeW (δ-phase) and Fe_7W_6 (μ-phase), and one meta-stable phase, Fe_2W (λ-phase) (Lassner and Schubert 1999 p39).

The phase diagram for the Fe-W binary system is shown in Appendix 12. The presence of tungsten in the prills of the slags from Butterbrook, Nosworthy and Wallabrook, which in each case is accompanied by some iron, can be explained by the fact that tungsten is a siderophile. This behaviour has been noted previously by other researchers: analyses presented by Earl (1986) of some of the prills from slags produced in his smelting experiments indicated that alloys of iron and tungsten had been formed.

Based upon the results displayed in Table 3.10, there does not appear be a linear relationship between the amount of iron and the amount of tungsten in prills containing both these elements plus tin. Depending upon the relative proportions of iron and tungsten present in the prill, different iron-tungsten phases may form within a matrix of iron. Additionally, as iron is to some extent soluble in tin, any iron not alloyed with tungsten may form hardhead, so the tin matrix may contain both iron-tin and iron-tungsten phases in a matrix of tin.

There are some prills, however, that contain tungsten in quantities that cannot be explained by the above theory. The level of iron in the Crift Farm prill appears slightly too low in relation to the tungsten content to form any of the iron-tungsten intermetallic compounds. As it is unlikely that the furnaces in use at Crift Farm were capable of generating the conditions necessary to produce metallic tungsten by direct reduction with carbon, another mechanism must be postulated to explain its presence. It is also necessary to consider another mechanism to explain the presence of high levels of tungsten that are accompanied only by tin in the prills from the Doe Tor Green slag. The composition of the slag from this site does not suggest a requirement for very high furnace temperatures, i.e. iron and titanium oxide contents are moderate. It may be,

therefore, that the tungsten is part of a more complex alloy, perhaps containing molybdenum as well as iron. Alternatively, small quantities of tungsten may have been produced by reductant gases other than carbon monoxide. Potassium cyanide is believed to be formed by the reaction of atmospheric nitrogen with alkaline compounds in charcoal ash (Louis 1911 p21, p26; Percy 1864 p447). Although present only in small amounts, potassium cyanide is a stronger reducing agent than carbon, thus could facilitate the production of metallic tungsten at lower temperatures.

The presence of prills composed of >95% tungsten in the slag from Carvedras also presents a problem. Although this is a reverberatory slag, which means the furnace probably operated at a higher temperature, if conditions at the time of smelting were sufficiently reducing to produce tungsten metal, then it would be expected that iron would also be reduced out of the slag, but iron is present in the two prills that were analysed in concentrations of no more than 1%. As there is only a single slag sample from this site, and this is of relatively small size, it is possible that prills with a high iron content were also generated, but have not been detected. Tungsten prills, having a higher density (19.35 g/cm^3) than tin (7.28 g/cm^3) or tin-iron prills (7.74 g/cm^3), would drop down through the slag more rapidly, so a partitioning of metal types might have occurred.

Tungsten and iron-tungsten phases within a tin matrix would appear as mottling or patchiness with SEM backscattered electron imaging (see p230). Examples of this were noted in the prills in slags from Doe Tor Green and Nosworthy.

The temperature of formation of the various iron-tungsten phases could potentially provide information regarding furnace operating temperatures, since the binary phase diagram for these two elements has been determined. However, the very small size of

the prills analysed in this work has meant that individual iron-tungsten phases within those prills could not be identified. No binary phase diagram for tin and tungsten exists, owing to these elements being so insoluble, so no information can be gleaned from the prills in the Doe Tor Green or Carvedras slags.

Molybdenum

No information is available on the role of molybdenum in tin smelting. Molybdenum lies below tin on the Ellingham diagram (see Figure 4.1, p392) so is more difficult to reduce with carbon, requiring, like tungsten, a very high temperature or a stronger reducing agent (industrially, reduction of molybdenum is achieved using hydrogen gas) (Cottrell 1995 p117). Compositional data presented in Table 3.10 indicates that molybdenum is not a common component of prills, and in those prills in which it does occur, it is present at levels of no more than c.2%. Prills containing 1-2% molybdenum often also contain >1% of either iron or tungsten, which would be expected as strong reducing conditions would also encourage the formation of metallic iron and tungsten. Modern industrial alloys containing molybdenum, tungsten and iron are known, so where these metals are detected in a tin prill, they may be present as interstitial phases in the same way that crystals of hardhead occur in a matrix of pure tin (Figure 3.43, p308).

4.1.3: The Evidence for Slag Recycling and its Implications for the Study of Archaeological Slags

During tin smelting, by whatever method this is achieved, some loss of tin to the slag is inevitable, this taking the form either of metallic prills physically trapped within the solidified slag, or as tin silicates chemically combined with it. Attempts to recover this

tin from slag have to be considered in terms of the economics of the day, but there are two basic methods by which this may be accomplished: by crushing slags to recover prills, and by resmelting the slags. Both these processes have implications for the study of archaeological slags. Crushing of slag is likely to reduce the amount of material available for study, while recycling slags back into the furnace will alter their composition. A further difficulty arises where slags are traded to other smelting works for re-treatment: the link between the slag, the type of furnace technology that generated it, and the geographical location of production, may be lost.

It is thus worth considering the extent to which slag reprocessing was carried out during different periods.

4.1.3.1: Slag Reprocessing in Blowing Houses

Analysis shows that blowing house slags contain high proportions of tin: sufficient to make them a valuable commodity. From at least 1624 Stannary Law prohibited the sale of tin ashes to plumbers or pewteres, but they could be sold to anyone else (Brooke 1998 p75). The sale of slag in 1725 by the widow of Francis Penneck, steward of Godolphin, is documented (RIC HEND Vol 14 p27) (which may explain the dearth of slag in the vicinity of Godolphin blowing house), and in 1724 Kalmeter describes an arrangement whereby a miner wishing not to sell his black tin could hire a blowing house to smelt it himself, covering the cost of labour and use of tools by paying a charge, amounting at that time to 20 shillings, and allowing the blowing house owner to claim any slag produced, which was reckoned to be worth a further 10 shillings (Brooke 1998 p66, p349).

The design of the tin blast furnace with its short shaft does not promote good slag-metal separation as there is insufficient time for the denser tin to settle out as the charge

moves down through the shaft (Smith 1996 p95), although some separation could occur after tapping if the molten slag was allowed to remain atop the tin in the float. The relatively high viscosity of some blowing house slags would compound the problem. Prill recovery would therefore appear to be expedient.

Indirect evidence for this can be found in the work of Beare (1586 p32) who makes reference to the grade of tin known as Pillion tin (see p143). As some prills could be composed of the tin-iron alloy hardhead, metal recovered in this way may have been of reduced quality and may have required additional refining.

Gerrard (1997 p115) notes that where blowing houses had facilities for stamping, these may have been used to crush slag.

From an archaeological point of view, crushing of slags would both change the nature of the material surviving at a site and reduce its quantity: powdered slag fragments are likely to have been swept away downstream during the washing process.

The presence of crushed slag residues in the tailings from a tin mill would, however, help to establish the difference between a stamping only mill and a blowing house where identification is in doubt.

The earliest British work that possibly refers to reprocessing by re-smelting is that of Beare (1586 p32), who notes that ‘waste’ is put in the furnace last, following different types of ores of decreasing quality. That re-smelting of slags was carried out is also suggested by his reference to ‘Sinder tin’ (see p143'). The fact that he calls this ‘corrupt tin’ suggests the quality of metal was inferior.

The method as it was practiced in Germany is documented by Agricola (1556 p416). Slag that was skimmed off the tin in the float during smelting was collected, washed,

and then broken up, either with hammers or under wet stamps. The crushed slag was then re-melted together with fine-grained tin ore. Slags might be crushed and re-melted three times.

Dr Cotton, writing in 1664, says of the black pitch-like 'cynders' that issue from the furnace, 'stamping it again together with the Tin stone, it adds to the Quantity of the Tin', which implies crushing following by re-smelting with fresh ore.

The Inquisitive Person (Anon 1670) states that slag is re-melted with charcoal, which would allow the furnace to be heated to a higher temperature than could be obtained with the mix of wood and peat charcoal the writer notes is used for ore smelting. (This change in smelting conditions is also seen in later blast furnaces: Thibault (1908 p223) notes that 19th Century German 'Altenberg' furnaces were run with stronger blast pressures when re-smelting slag). Again, there is a suggestion that the metal produced was inferior, as the writer states, 'When all is melted down and remelted there sometimes remains a different Slag in the bottome of the Float, which we term Mount-Egge; And that it is mostly an iron body, though of a Tin-colour, I assured myself by applying one of the Poles of a Loadstone to it, which quickly attracted it, yet not such a quantity by far, as that of Iron'. This would appear to be a description of hardhead.

Writing in 1724, Kalmeter (Brooke 1998 p348) reports that slag that is taken off the top of the molten tin that has flowed out of the furnace 'is later smelted once more, but the slag which arises in this second smelting is stamped and dressed, so that the tin prills can be taken out.'

4.1.3.2: Slag Reprocessing in Reverberatory Furnaces

As discussed above (p402) the layer of slag, sometimes called the 'pulled slag', which formed in a reverberatory furnace, was, from at least the 19th Century, considered to consist of three parts. The uppermost third (waste or top slag) was scraped off and discarded. The slag beneath this (middle slag) was mechanically crushed in order to recover entrained prills. Directly over the molten metal, the layer of metal-rich slag (bottom slag) was recycled by re-smelting.

'Glass' slag was taken off the surface of the metal in the float. Kalmeter reports in 1725 that it was put aside for later re-smelting (Brooke 1998 p346), but Barton reported that normal 19th Century practice was to discard it except for any pieces that had tin metal adhering, which were stamped and then re-smelted (Barton 1968 p348). By the late 19th Century techniques improved such that re-treatment of all glass was routinely carried out, with smelters buying the slags from other companies. Examples of later glass slags are therefore unlikely to be represented in the archaeological record.

As the accounts summarized in Table 4.3 attest, the recovery of prills by mechanical separation continued up to the 20th Century, provided that the metal thus recovered was of reasonable quality (Thibault 1908 p6). Pryce (1778 p283) gives a detailed account of the treatment of the portion of slag that remained in the furnace after smelting: '…It is carried to the stamping mill in order to separate the globules of melted Tin disseminated through the scoria or slag. The scoria being broke by hammers to the size of goose eggs, are put into the first stamping mill, and passed through small Iron Bars... By this means the pillion (for so all Tin recovered out of the slags is called) of the larger size is taken out, and thereby prevented from waste by too much stamping. The refuse of this first stamping is put into other stamping mills of a second, a third, or even

some part thereof into those of a fourth size… Of the pillion so separated, all the rough or grainy parts are considered as metal, and refined accordingly by being smelted without any flux, and the product of this smelting refined with the tin first tapped. The sandy and slimy parts of the pillion resembling stamped Tin Ores, are treated as such, and are mixed and smelted with them.'

From the inception of reverberatory smelting, it appears that slag re-smelting may have been carried out as a separate process to ore smelting. Kalmeter (Brooke 1998 p71-2, p345-6) describes how 'with the re-smelting of slags they let the metal out more often [than for smelting ore], mostly every quarter of an hour, making ingots of about 50 lbs (23 kg) weight, and all from a small cart load of slag, which they put in all at once… With slag smelting the culm is thrown in separately afterwards… When smelting slag they let the metal out as soon as it becomes molten… None of the slag produced by this second smelting runs out, but is raked out through the door by the chimney; it is not smelted any more but is stamped small and put on one side to be brought in again with other smaller or larger pieces.' Interestingly, however, Pryce (1778) makes no reference to a separate slag smelting.

Louis (1911 p24) notes that slag reprocessing is carried out by 'smelting the slags at high temperatures, either in shaft or reverberatory furnaces, sometimes with the addition of strong bases, such as lime, or of iron, or the tin-iron alloys…, or of bodies (such as oxide of iron) that will yield iron in the furnace. Generally this operation has to be repeated more than once, and the tin produced is much less pure than that obtained in the smelting process proper; it is in many places spoken of as 'slag tin'. This is the process of slag treatment proper, but in most methods of conducting the smelting

process, the richer slags, together with any by-products rich in tin and free from injurious ingredients, are added to the ore-smelting charge.'

The Two Stage smelting process commonly used in the 19th and 20th Centuries consisted firstly of an ore smelt (sometimes with iron drosses and hardhead included in the charge) carried out at c.1200°C, which generated tin containing c.2% Fe and slag with 10-20% Sn; subsequently a separate slag smelt (often with a lime flux) was carried out at temperatures up to 1400°C, producing hardhead with a composition of 20-55% Sn and 30-55% Fe and a waste slag of 1-2% (Smith 1996 p97).

As a result of there being several different types of slag generated in reverberatory furnaces, each of which was treated differently, and there being no real consistency regarding recycling practice, it may not be possible to effectively characterize reverberatory slags occurring in the archaeological deposits.

The transfer and sale of slags continued once reverberatory furnaces came into use. The carriage of 36 tons of slag from Newham (SW829441) to Calenick (SW820440) in 1704 is documented; these apparently were crushed and sieved (Henderson 1912; Tylecote 1980a). In 1711, the accounts of Calenick refer to the purchase of 'cinders' (Tylecote 1980a). Barton (1968 p136) notes that Seleggan (SW695402) works bought slag from Redruth in 1892-3. Later, the slag dumps at Seleggan, which closed in 1931, were taken for re-working, probably at Liverpool or Hull (Earl 1991 p75). Smith (1996 p95) also draws attention to the fact that in the 19th and 20th Centuries Cornish tin slags were purchased by manufacturers of lead and copper alloys.

4.1.4: Application of Slag Analysis in the Identification of Unknown Slags

One of the principal findings of this work is that it is not as easy to distinguish between slags deriving from different types of furnaces as some authors have suggested. There are other factors beside the type of furnace in which the tin was being smelted that determine the physical appearance and chemical composition of a slag, and these interact in complex ways, so that no one particular feature can be said to be characteristic of early, blowing house or reverberatory slags.

There follows a discussion on how the interrelation of different slag characteristics can be utilized to suggest what type of technology is likely to have been in use.

Of all the slags that were analysed, representative samples were obtained from six sites that either could not be attributed to any particular period of history, or where the dating of the site was ambiguous.

Metherel

The first site to be considered is Metherel, now on the edge of Fernworthy reservoir. Although the slag and supposed tinstone were found inside two round houses of probable Bronze Age date, they were retrieved from the same stratified context as a coin dating to c.1500 and pottery from a similar period, prompting Worth, who led the excavation, to propose that the smelting remains had been deposited by tinners re-using the shells of the ancient buildings as stores (Worth 1935, 1937). He commented upon the similarity of this slag to that from ‘the old blowing houses’, by which it might be assumed that he believed the slag to be contemporary with the coin and pottery. However, while observing that one round house contained a stone that may have been

used as an anvil to break up slag, he did not venture to put forward any theory as to how the slag came to be deposited within the buildings.

A number of possible explanations may be tendered: the slag could have derived from a blowing house that operated in the area in c.1500 and was taken to the ruins of the round houses to be broken up to recover trapped tin prills; it could be waste material from a small illicit smelt carried out by the tinners who wished to avoid paying coinage duty; or it could be the product of an early smelting process that, having been unearthed by tinners during a streaming operation, was taken back to their shelter as they recognized that the tin it contained was valuable and recoverable.

There are problems with the idea that the slag derived from a blowing house. Firstly, the only known blowing house in the immediate vicinity of Metherel is Thornworthy, some half a kilometre away, and a comparison of the samples from these two sites reveals clear differences in both physical appearance and chemical composition. For example, the Metherel slags are glassy, with morphologies suggestive of a viscous melt; surface weathering has produced a thin coating of gold-coloured hydrogen glass. Under the microscope, flow banding is clearly visible, and at very high magnifications crystals c.5μm across are observed. Metallic prills are relatively common and unusually large, measuring up to 0.5mm. By contrast, the Thornworthy slags have silky lustre, which results from a dendritic microstructure, and the outer surfaces of many samples are iron-stained. Their morphologies are consistent with a low viscosity melt. Prills are rare, and very small.

Compositionally, the Metherel slags have extremely high tin oxide contents (c.55-60%), fairly low iron oxide (c.10%) and minimal TiO_2 (1-2%), while the Thornworthy slags have low SnO (c.5-18%), high FeO (23-34%) and high TiO_2 (c.12%).

Although it is possible to argue that the slags differ because they were produced in blowing furnaces using different ores, or that one slag is a first smelting slag and the other a product of slag recycling, or that there was some problem with the smelt that caused a high loss of tin to the Metherel slags, the extent of the differences between the Metherel slags and those from Thornworthy and other definite blowing house sites in that part of Dartmoor is so great as to make this seem unlikely.

Another problem with a blowing house origin for the Metherel slag becomes apparent on attempting to explain its presence in the round houses. It is documented that tin rich slags were returned to the furnace for re-smelting (Cotton 1664), but the Metherel slags would seem from their very high residual tin content not to have been subjected to recycling, and it is difficult to see any practical reason why, if they are blowing house slags, they should have been removed from the blowing house before that process could be carried out. Slag was a valuable commodity and belonged to the blower (see p421) so, leaving aside theft, it is hard to explain why potentially valuable material would be taken elsewhere.

The high loss of tin to the Metherel slag suggests a gently reducing atmosphere during smelting, and it is unlikely that such conditions would have appertained in a blowing house in north-eastern Dartmoor, where high melting point, low viscosity slags would be generated. The second possibility – that late Mediaeval tinners were attempting to smelt their ores illicitly, using a small hand-blown furnace – must therefore be considered.

While tinners may have stored ore in the round houses merely for safekeeping, never intending to smelt it themselves, the juxtaposition of alluvial cassiterite pebbles alongside pieces of slag would have lent support to an on-site smelting scenario. That

the pebbles proved to be schorl, not cassiterite, severely weakens that argument, if not entirely invalidating it.

Finally, therefore, the possibility that the slag is from an earlier period will be examined. The Metherel slag certainly has characteristics that are consistent with a pre-blowing house origin. It has plentiful large prills with few impurities, which suggests gently reducing conditions. Its low iron and titanium contents, which are not typical of slags from this part of Dartmoor, may indicate handpicking of clean alluvial cassiterite. The tiny crystals visible at high magnification, although too small to analyse, might possibly be cassiterite, which is either unreduced or has precipitated out of the melt; similar crystals have been observed in the Bronze Age slags from Caerloggas. Another similarity with the Caerloggas slag is the extent of surface weathering. Worth (1935) describes the Metherel slags as 'mainly pale ochreous in colour', adding that 'the smaller pieces are ochreous throughout'. Biek (1978), who carried out analysis of the Caerloggas slag, showed this discolouration to be 'hydrogen glass' i.e. almost pure silica. It has also been noted on samples from Whitten Knowles and Crift Farm, both relatively early sites, but also on a small number of samples from Upper Merrivale, so while surface deterioration may be displayed by early slags, it is not an infallible indicator of great age.

How early slag came to be associated with 14th/15th Century ceramics can be explained if it is assumed that in the prehistoric period tinners smelted their black tin next to the streamworkings. Later tinners may then have found these deposits of ancient slag when reworking the same streams, as the many reports of prehistoric finds recovered from streamworks demonstrate that they did (see Sections 1.4.1 to 1.4.4). It is probable that if scatters of slag were found the tinners would recognize that it contained recoverable

quantities of tin, and that it was worth their while to collect the slags and take them to be re-smelted, or to crush them for prills that could subsequently be melted down.

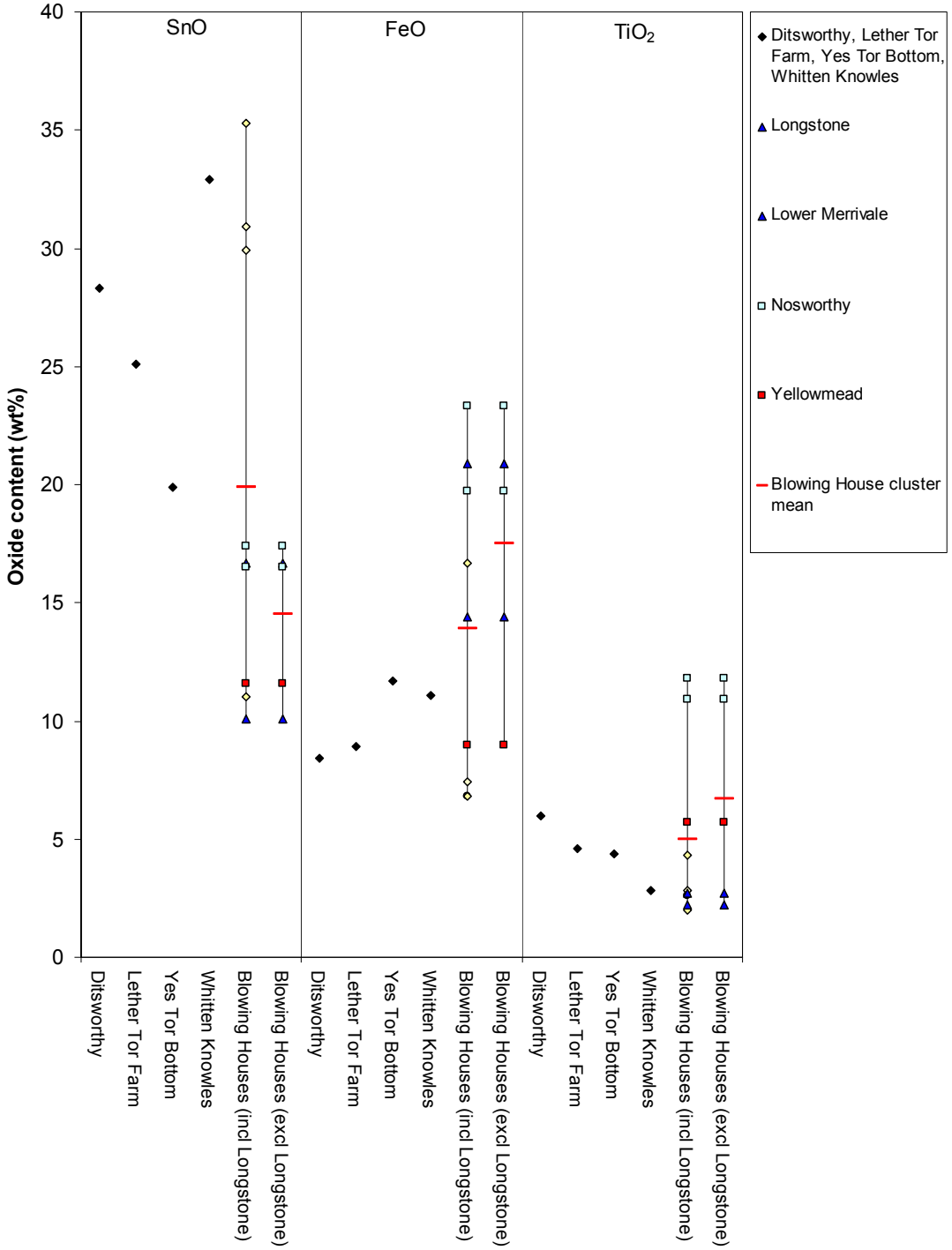
The Metherel find may thus be a collection of ancient tin slag, stored ready to be broken up or taken for re-smelting, but never re-claimed.

Yes Tor Bottom

Another slag find, from Yes Tor Bottom, has been discovered in similar circumstances: the slag was recovered from one of a group of prehistoric round houses, but again is associated with 14th or early 15th Century pottery rather than prehistoric artefacts (Baring-Gould et al 1898; Worth 1940). The same arguments may thus be put forward to explain the origin of this slag, but while it is possible to argue that the Metherel slag is early on the basis of compositional differences, it is much harder to distinguish slags of different periods when they derive from more western parts of Dartmoor, owing to the fact that indicators for identifying early slags are not dissimilar to the compositional characteristics determined by that geological setting.

The Yes Tor Bottom samples have the glassy flow banded microstructure of a high viscosity slag, and prills are pure tin and relatively common, though none of exceptional size were observed, all of which could be accounted for simply because local low iron ores were used. One feature of this slag that is somewhat out of the ordinary is that it also contains rare clusters of pale crystals – as yet unidentified – which may be cassiterite grains, and these, as noted above, have thus far only been identified in the pre-blowing house slag from Caerloggas. However, though the Yes Tor Bottom slag does have a relatively high SnO content (c.20%), it is not so obviously tin rich as slags that are known to be early, levels being within the range seen in neighbouring blowing houses. That being said, at this point it is worth noting that the

Figure 4.4: Comparison of Key Chemical Species in Slags from Western Dartmoor



extremely high tin content in the slags recovered from around Longstone blowing house makes a determination of origin based on tin content very difficult. If the data

from Longstone are disregarded, the tin content of the Yes Tor Bottom slag (and the other slags discussed below) exceeds the range for blowing houses (see Table 4.4). The relatively low FeO and TiO_2 contents of the Yes Tor Bottom slag (c.12% and c.4% respectively) are also similar to those seen in some of the blowing houses in the vicinity: e.g. Lower Merrivale, Longstone and Yellowmead. For a comparison of the compositions of these chemical species in slags from the area in question, see Figure 4.4.

Ditsworthy

The same difficulty associated with geographical location arises when considering the collection of five pieces of slag held by Torquay Museum of Natural History: another potentially early assemblage of material. No information is available relating to the circumstances surrounding the find, and the slag is recorded only as having come from 'Ditsworthy' in 1949.

Ditsworthy Warren, situated in southwest Dartmoor with the approximate OS grid reference SX5866, encompasses the prehistoric settlement and stone rows of Whitten Knowles, where a scatter of slag believed to be of early date was found. No historically documented smelting sites lie within the bounds of the warren: the nearest are Yellowmead (blowing house) and Eylesbarrow (blowing and reverberatory furnaces).

When the slag from Ditsworthy is compared to samples from these other sites, it is seen to bear the greatest similarity to that from Whitten Knowles (although the difference in their surface weathering suggests that they do not come from the same place): both are high tin glassy slags with distinct flow banding, and both contain unusually large prills. While the single prill analysed in the Ditsworthy slag proved to be antimony, it is likely that these samples do also contain tin prills, given the c.28% SnO content of the slag.

Again, despite this rather high SnO content, it must be noted that it is exceeded by the levels found in several of the samples from the blowing house at Longstone, which lies only c.3km to the north. In all other respects, the compositions of the Ditsworthy slag and slags from sites of all periods in the immediate vicinity are not markedly different: FeO content is lower than the mean value for blowing houses in the area, but only marginally. Finally, it may be noted that no isolated cassiterite crystals or alumino-silicate rings/clusters, which appear to be features of pre-blowing house slags, were observed in the slag matrix of the single Ditsworthy sample examined.

Table 4.4: A Comparison of Key Chemical Species in Slags from Western Dartmoor

Site	**SnO (wt%)**	**FeO (wt%)**	**TiO_2 (wt%)**
Ditsworthy	28.3	8.4	6.0
Lether Tor Farm	25.1	8.9	4.6
Yes Tor Bottom	19.9	11.7	4.4
Whitten Knowles (Early Site)	32.9	11.1	2.8
Blowing House Mean	19.9	13.9	5.0
Blowing House Range	10.1 – 35.3	6.8 – 23.3	2 – 11.8
Blowing House Mean excluding Longstone	14.5	17.5	6.7
Blowing House Range excluding Longstone	10.1 – 17.4	9.0 – 23.3	2.2 – 11.8

Note: For the purpose of this comparison data from the blowing houses at Longstone, Lower Merrivale, Nosworthy and Yellowmead has been used. The figures presented are biased owing to different numbers of samples from these sites having been analysed.

Lether Tor Farm

Not far from Ditsworthy, on the northern side of what is now the Burrator Reservoir, is Lether Tor Farm, another site to have yielded slag of questionable origin. The material, which was found in soil above a disused potato hole, is from a location not directly associated with any known smelting activity. It lies barely a kilometre from the tin mills at Nosworthy, but despite the close proximity of the two sites, the slag samples from

Lether Tor Farm and Nosworthy are quite different. The former is a glassy slag with flow banding, while the latter is a phased slag, its more crystalline nature a result of its relatively high titanium content. Samples from both sites contain some large prills, but the prills in the Lether Tor Farm slag are tin with only traces of other elements, while the Nosworthy slag has small amounts of both iron and tungsten in one of the prills analysed; the latter site thus appears to have employed more strongly reducing conditions for smelting.

As with the Yes Tor Bottom and Ditsworthy slags, at c.25% the Lether Tor Farm slag has a SnO content on the high side when compared to blowing houses in western Dartmoor (as ever, with the exception of Longstone). Similarly, its FeO content is lower than the mean for blowing houses.

Wapsworthy Newtake

The find of slag at Wapsworthy Newtake, or Jack Cloke's Prospect as the site has also been called, is interesting in that previously no other remains relating to smelting have been located anywhere in this remote part of Dartmoor, although there are spoil heaps aplenty to indicate mining activity. The nearest blowing houses are Upper Merrivale to the south, and Doe Tor Green to the north, and it is against these than the slag from Wapsworthy will be compared. Both are some 4km distant, which means that the cluster of sites under consideration is both smaller and occupies a larger area than for the previous examples, but of necessity it must suffice.

A group of five pieces of slag was found on a spoil heap, and a further three pieces about 35m away, each at different spots (Munro 2004). The slag's discoverer, Deric Munro, has offered some possible explanations for the presence of slag at this location. The first is that the slag resulted from ore assaying, evidence for which is reported to

have been found in the remains of a relatively modern hut in the area (D. Munro pers comm. 5/4/04), though he considers this doubtful as individual slag fragments seem somewhat too large to have formed in a crucible: the largest has a mass of 25g and has broken edges so was originally part of a larger whole (D. Munro pers comm. April 2002). The second explanation is that the prospector, Jack Cloke, attempted to smelt his own ores.

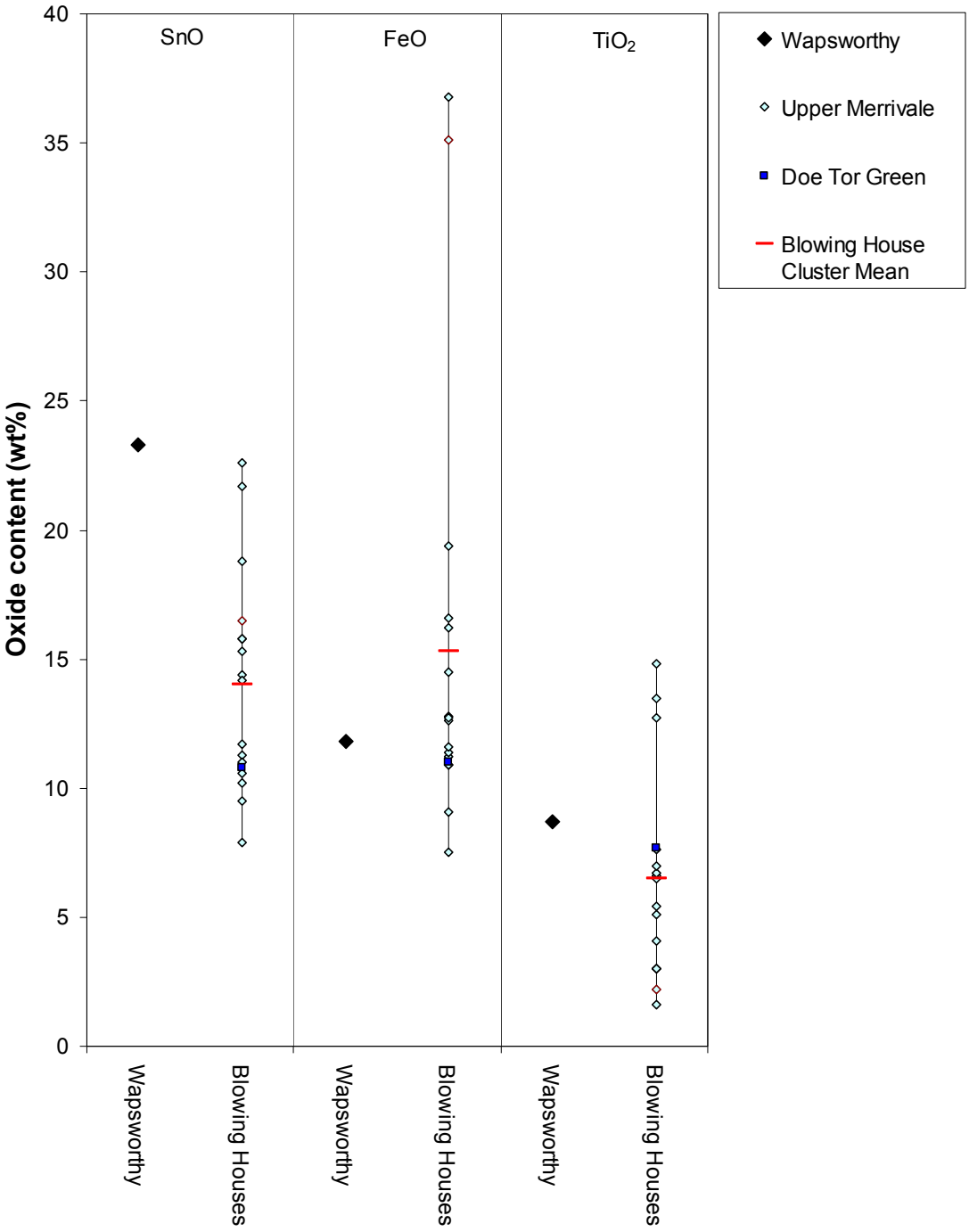
Whether produced by Jack Cloke, or some unknown tinner working the cassiterite deposits in an earlier period, the slag has some characteristics that hint that it is not dumped waste from a blowing house. Its morphology is that of a high viscosity slag, and it exhibits flow banding within a glassy matrix. This in itself is inconclusive, for in this respect it is similar to the Doe Tor Green slag, though that material appears to have a silky lustre owing to its having a microstructure in which a small amount of a feathery phase is present. The Upper Merrivale slags further complicate matters: the physical characteristics of these slags are varied, the majority having a feathery phased microstructure, though glassy slags are also relatively common, with flow morphologies occurring in c.15% of the samples examined.

More tellingly, when examined under the microscope a small number of dark needle-like crystals a few micrometers long, the composition of which was not determined can be seen around some of the inclusions in the Wapsworthy slag. Thus far, similar dark crystals have only been observed in the pre-blowing house slags from Caerloggas and Crift Farm.

Prills are relatively common in the Wapsworthy slag, and the sample contains at least one relatively large prill, which is tin with only minor impurities. The prills in the slag from Upper Merrivale blowing house are also good quality tin, but prills are rare and

generally small. The Doe Tor Green slag also has some quite large prills, but fewer over all, and these have a mottled appearance owing to their being contaminated with tungsten.

Figure 4.5: Comparison of Key Chemical Species in Slags from Northwestern Dartmoor



The Wapsworthy slag has quite a high SnO content (c.23%), which is double what is seen in the slag from Doe Tor Green, and is higher than the mean for Upper Merrivale blowing house slags (c.14%), although there are some individual samples from Upper Merrivale with comparably high tin contents. These data are shown in Table 4.5. Other chemical species are not greatly different from those seen in the blowing houses. For a comparison of compositions, see Figure 4.5.

Table 4.5: A Comparison of Key Chemical Species in Slags from Northwestern Dartmoor

Site	SnO (wt%)	FeO (wt%)	TiO_2 (wt%)
Wapsworthy	23.3	11.8	8.7
Blowing House Mean	14.0	15.3	6.5
Blowing House Range	7.9 – 22.6	7.5 – 36.8	1.6 - 14.8

Note: For the purpose of this comparison data from the blowing houses at Upper Merrivale (except sample 2/25) and Doe Tor Green has been used. The figures presented are biased owing to different numbers of samples from these sites having been analysed.

Despite the difficulties involved in identifying features characteristic of any particular production technology in slags from western Dartmoor, on balance it may be suggested that the samples from Yes Tor Bottom, Ditsworthy, Lether Tor Farm and Wapsworthy Newtake are not the result of smelting in a blowing house, since all have some features that have previously only been noted in definite pre-blowing house slags, or that fall at or beyond the extremes of the range seen for blowing house slags.

Drakeford Bridge

The final piece of slag of unknown origin to consider comes from Drakeford Bridge on the eastern edge of Dartmoor, where it was discovered on the bank of the River Bovey. There is no documentary evidence for a smelting site the vicinity of this find (T. Greeves pers comm. Feb 2002). The nearest known sites are the blowing houses at

Lustleigh and Blackaller. The slag occurs as relatively large pieces, with a morphology suggesting a fairly low viscosity. It has a silky lustre owing to its dendritic microstructure, and apparently is free of prills. Compositional analysis shows it to have a moderate tin oxide content, with high iron and titanium. It thus exhibits no features characteristic of early slags, although as no slag has so far been recovered from any identifiably early site in eastern Dartmoor, it cannot be said for certain that a pre-blowing house slag from this area would show the same qualities as early slags from sites elsewhere in Devon. The effect of changing ore geology on blowing house slags has been demonstrated, so there is a possibility that the high occurrence of iron in local ores would also lead to differences in early slags, but to what extent remains a question that cannot yet be answered; the more gentle reducing conditions in early furnaces may not have been sufficient to co-reduce iron.

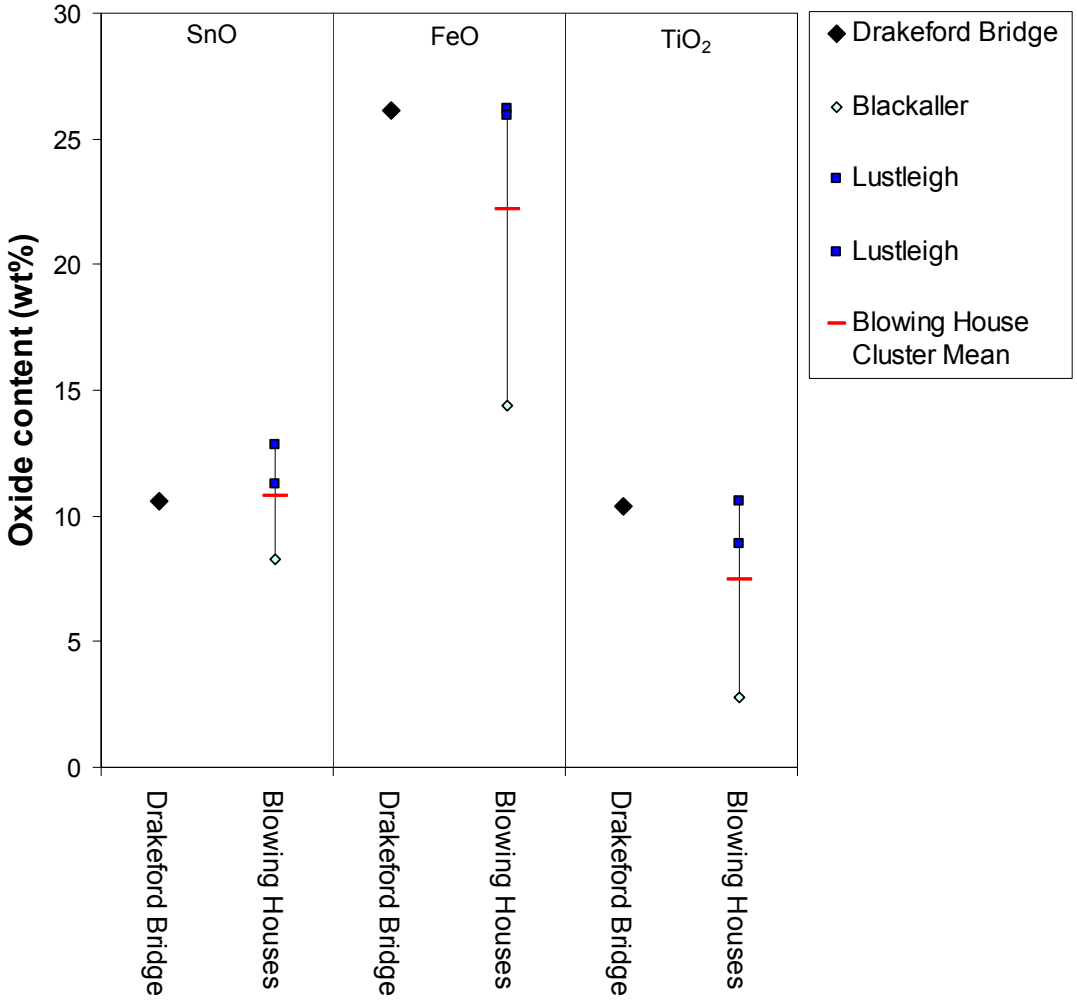
The Drakeford Bridge slag is similar in appearance to the Lustleigh samples and has a composition falling within the range of the slags from both neighbouring blowing houses, see Table 4.6 and Figure 4.6. It is therefore likely that the Drakeford Bridge slag also derives from a blowing house, and although there is a chance that the slag is dumped waste, the riverside location of the find site raises the possibility that there may be an as yet unrecognized blowing house or stamping mill in the vicinity.

Table 4.6: A Comparison of Key Chemical Species in Slags from Eastern Dartmoor

Site	SnO (wt%)	FeO (wt%)	TiO_2 (wt%)
Drakeford Bridge	10.6	26.1	10.4
Blowing House Mean	10.8	22.2	7.4
Blowing House Range	8.3 – 12.8	14.4 – 26.2	2.8 – 10.6

Note: For the purpose of this comparison data from the blowing houses at Blackaller and Lustleigh has been used. The figures presented are biased owing to different numbers of samples from these sites having been analysed.

Figure 4.6: Comparison of Key Chemical Species in Slags from Eastern Dartmoor



The morphology of the Drakeford Bridge slag could occur if it had a reverberatory furnace origin, since it appears to have been very fluid. However, examination at the microscopic level suggests that this was not so: many reverberatory slags have microstructures comprising discrete crystals, which the Drakeford Bridge slag lacks, but having said this it is also true that dendrites may also occur, so this lack is not conclusive. It is not possible to distinguish between the Drakeford Bridge slag and a reverberatory slag on the grounds of chemical composition, but as there is no record of a smelting house in the area, if the samples were from a reverberatory furnace they must have been brought in from elsewhere and dumped.

4.2: Ores

The ores that have been analysed, both here and in other works, are for the most part good-sized pebbles of alluvial cassiterite, mainly associated with prehistoric sites, and as such are far from representative of the ores that would have been in use for much of the past millennia. Given their size and quality, it raises the question as to why such pebbles survived to be found, rather than being smelted for the tin they contain. It may be that particularly large specimens were picked up whenever they were noticed and taken back to the settlements to be hoarded until enough ore was obtained through streaming to justify building and running a furnace. Rarely, circumstances would conspire to prevent the collected ore being used.

It is necessary to consider whether such ores were destined to be smelted directly. There is clear evidence from the Bronze Age through to the Dark Ages for bronze working in early settlements (as summarized in Sections 1.4.1 to 1.4.4), and the fact that cassiterite pebbles have been found in metal-working workshops, but other evidence of tin smelting is absent, has led to it being suggested that bronze could have been produced in crucibles by adding cassiterite to copper metal, rather than direct alloying of metallic tin and copper (Tylecote 1978 p51). Charles (1978) discusses a range of chemical reactions by which alloying might be accomplished.

The existence of tin metal objects in the archaeological record demonstrates that the technology to smelt tin as a metal in its own right was available; however, if the process was separate from bronze production, demand would have been lessened and tin smelting may only have been performed on a relatively small scale. Additionally, the specimens of ore found in settlements, if indeed these were intended for use in alloy formation, may have been different from the ores that were smelted.

The sample from Crift Farm does not have the rounded shape of water-worn alluvial cassiterite; it may be eluvial or 'shoad' ore (see Section 1.3.2).

There is a definite lack of ore from later smelting sites, and one reason for this bias is likely to be that excavations of Mediaeval and later smelting sites have been few and far between. Even with the most careful handling of the ore, it is unlikely that every fragment brought to the smelting site would end up in the furnace. Dumps and scatters of spilled ore must have existed. The problem faced by the archaeologist is that the remains of any such dumps are inaccessible without excavation, and small fragments that are exposed by natural erosion, in contrast to slag fragments with their rather distinctive appearance, will more often than not go unrecognized, cassiterite being hard to identify visually. Additionally, as the 'ore' in the dump at Upper Merrivale suggests, large dumps surviving at a site will almost certainly contain material that was deemed too poor to process, as opposed to representative samples of good ore waiting for stamping or smelting.

In consequence, any study linking ore composition to final slag composition, would be severely limited. Following from the analysis of the samples available, however, some comments can be made.

Alluvial pebbles can be rich in cassiterite (>60% SnO_2), but still contain crystals of gangue minerals of varying size. Crushing and washing is unlikely to remove all of the gangue, with the result that even good quality ores will produce some slag or leave some siliceous residue behind.

A correlation might be expected between the size and types of gangue mineral occurring in the ores and the residual mineral inclusions present in the slags from the

same sites. In fact, no clear relationship is seen, but this is probably down to the very diverse nature of the samples and the limited number of analyses carried out.

Mineral inclusions are actually quite rare in the Caerloggas slag, but one was present that was visible to the naked eye, which is consistent with the observation that alluvial pebble 4/13 contained crystals up to 2mm in diameter.

None of the inclusions in the Caerloggas slag were analysed for the present study, but previously Salter (1997) determined that the residual mineral inclusions in this slag were zircon. However, analysis of individual crystals in the Caerloggas ore samples failed to reveal any crystals composed of this mineral (see Tables 3.14 and 3.15). Crystals of gangue minerals present in the pebbles were tentatively identified as biotite mica and feldspar, based on the results of the SEM analysis, while XRD analysis detected quartz as a fairly major constituent.

Compositional data for inclusions in the Crift Farm slag is lacking. Inclusions up to 0.5mm across are relatively common in slag from this site. The single sample of ore recovered from Crift Farm contains no crystals of this size, and thus can be said to be unrepresentative of the ores normally in use at this site.

Returning briefly to the issue of supposedly high titanium contents in Dartmoor slags, it may be noted that in none of the ore samples, whether deriving from Devon or Cornwall, was TiO_2 detected at levels greater than 0.3%.

Finally, the misidentification of the stream tin pebbles from Metherel hut circles is interesting as it casts doubt on the assertion that this site was used for smelting (see Section 4.1.4).

4.3: Furnace Wall and Lining Materials

It is generally accepted that blowing houses were fashioned from slabs of granite. The few examples of surviving furnace structures on Dartmoor (see p133-37) support this assertion, and to this may be added the evidence of fragments of slagged granite found at several other sites that appear to have been chipped out of the furnace after smelting (see p447).

Documentary evidence on the subject is relatively scant. Neither Beare (1556) nor Carew (1602) comment upon the material from which furnaces are built. Dr Cotton's 1664 account of smelting is silent on the nature of the furnace body, and describes the float only as a 'stone trough'. Meanwhile, the anonymous writer of 1670 appears to suggests that furnaces were not constructed of granite, stating 'our Lime, though the strongest I ever yet heard of, as being made of the hardest Marble, will not endure the fire in our Hearth, but we must use a particular kind of Clay'. It is not until the 18th Century that specific reference is made to building materials: Kalmeter (Brooke 1998 p66, p347), Pryce (1778 p136) and Hatchett (Raistrick 1967 p25-6) all note that blowing house shaft furnaces were constructed of granite (moorstone); firebricks were used for reverberatory furnaces (though in the 18th and early 19th Century the outer shell of these structures might be granite (see p167, p185)). Modern blast furnaces outside the UK often use brick-lined cylindrical iron or steel shafts (Mantell 1949 p125), and Ure (1853 p855; 1875 p1005-6) describes such a design, but the blowing houses of Cornwall went out of use around the time this innovation was being introduced.

Granite has several advantages as a furnace material. It is non-porous, thus there is no penetration by slag (see p448) and damage to the rock by chemical reaction with the slag is therefore limited to the immediate surface. It is highly refractory and thus will

withstand elevated temperatures; additionally, eventual vitrification only serves to reduce porosity of the rock further. It is composed mainly of silicate and alumino-silicate minerals which, when they react with the slag and are incorporated into it, do not increase the basicity of the slag as calcium rich minerals would, causing tin to act as an acid and become trapped in the slag through the formation of stannates or silico-stannates.

No blowing house furnace survives with its front wall intact, which has led to the suggestion that this part of the structure was temporary, and was either formed of clay (Gerrard 2000 p129) which was broken up after each smelting, or that a slab of granite luted into place was used (Earl 1991), allowing easy access to the interior of the furnace so that repairs could be effected. Documentary sources appear to concur: Kalmeter (Brooke 1998 p65) noted that the front of the furnace was taken down after each smelting.

That damage occurred to furnaces is documented, e.g. by Beare (1586 p108) who noted that the front wall of the furnace could be damaged if the blast was too fierce, and by Agricola (1556 p416) who stated that there would be damage to the furnace after it had been operating at high temperature for three days (a German furnace being run for longer than its English counterpart).

It is usually assumed that the interior of the furnace was completely lined with a clay lute. The presence of a refractory lining serves two main purposes: to seal the furnace so that metal cannot escape through its sides and base, and to protect the furnace structure against chemical attack by the slag generated during smelting.

Certainly some clay was used in furnace construction, as the anonymous writer of 1670 clearly states (see p444). Kalmeter states categorically that clay lined the shaft (Brooke

1998 p66, p347), while Pryce (1778 p136) merely states that clay is used in blowing house furnace construction but makes no specific mention of a lining. Hamilton-Jenkin (1927 p71) suggested that expenses for 'building the house' that occur between 1 and 7 times per quarter in the accounts of St Austell Old Blowing House (c.SX009526), which worked in the second half of the 18th Century, could refer to the periodic replacement of the furnace lining. A similar reference to 'making ye house seven times' occurs in the accounts of St Blazey New Blowing House (c.SX0653) (Barton 1968 p132). There are several references in 18th Century accounts and inventories of smelting works to 'blowing house clay', e.g. 12 tons were bought for Newham (SW829441) in 1703 (Tylecote 1980a), while in 1760 Angarrack (SW583382) had 14 tons in stock (Higgans 1979). Whether this material was used solely in blowing houses or whether the term had devolved into a general description of a particular refractory material remains open to question. Given the large quantities in stock at these two works, which mainly ran reverberatory furnaces, the latter would seem likely. At Treyew (SW8144), another smelting works with a blowing house on site, was a 'mill for grinding clay + culme' (CRO/DD/EN 623/1) (Gerrard 2000 p134).

Figure 4.7: Fragment of slagged furnace material from Week Ford with possible clay layer.

Archaeological evidence for clay lined shafts comes from Upper Merrivale (SX55187665) and Avon Dam (SX67226553), where linings have been found in situ (see p136). The presence of fragments of slagged material within the layer of unburnt clay that lines the base of the Upper Merrivale furnace points to removal and replacement of old linings (Greeves 1995). A sample from Week Ford (SX663723) found by Greeves has a possible dried clay layer between the granite block and the slagged layer (Figure 4.7), but equally the material may be quartz crystals from heat damaged granite. Earl (1989) suggests the lute used at Week Ford was clay mixed with charcoal, as a lens of this material was found amid ore tailings from the mills. A sample from Avon Dam is more obviously composed of some refractory material with slag adhering to it (and other similar examples have been reported from this site (R Smerdon pers comm. 30/1/05)).

It is perhaps surprising that fragments of furnace material are not more common in the archaeological record. This may simply be down to the lack of excavation at blowing house sites; after all, the excavations at Upper Merrivale yielded around 150 pieces (T Greeves pers comm. 2002). However, some material may have been recycled back into the furnace. Agricola (1556 p416) recounts how, after smelting, the old lining could be removed with hammers, the interior of the furnace refitted with sandstone and a new lining put in; the old lining was afterwards crushed for reprocessing. There is no reason to presume that English practice was otherwise.

The samples of furnace material examined for this work were recovered from sites dating to the Post-mediaeval period and later. All the fragments from the Devon blowing houses were granite, with one exception. A piece of slagged sandstone found at Upper Merrivale is so far unique, but there is no reason why this material could not

have been utilized. Its use in Germany is recorded by Agricola (1556 p411), who notes that furnaces are constructed of 'broad sandstones, or of those common substances which by nature are composed of diverse materials' [this latter is probably a reference to granite]. It is reasonable to suggest that granite was the building material of choice for English blowing houses both because its physical properties made it suitable and because it was so readily available.

A single example of firebrick was obtained from 19th Century Eylesbarrow (SX59196765), though other samples from this site were composed of granite. This smelting works housed both types of furnace, the outer structures of which were built of granite, and while the reverberatory furnace is certainly associated with dumped firebricks, it is thought that the granite shell of the shaft furnace might also have had a lining of firebrick (Cook et al 1974) (see p185). Which furnace the samples derived from is thus hard to determine.

The samples analysed herein were probably chipped off a larger block, probably while repairs were being made to the furnace. All have similar features: slagging occurs only on one face, beneath which is found a vitrified layer; the opposite face shows evidence of heat-damage in the form of reddening and/or increased friability.

Examination of the microstructure of slag layers reveals that the slag is often phased. This is not unexpected: compositional analysis (see Section 3.3.3) indicates that iron and titanium are abundant constituents of the slag in these areas, and these ions, as discussed on p380, promote dendritic phase formation.

The layer of slag on the surface of the block is very thin: 2mm at most, and usually less than 1mm. X-ray maps of tin distribution (see Section 3.3.2) suggest that penetration of slag into the granite between crystals does not occur: the granite is impermeable to the

slag. Mapping also appears to suggest that there is no mixing of molten fluids at the slag/granite interface: if mixing occurred it would be expected that levels of tin would decrease gradually from the outer slagged surface into the granite, but in fact the change is relatively sharp.

That individual crystals from the granite are visible both with the naked eye and using X-ray mapping of silicon suggests that these silicate minerals are not becoming wholly fluid. The relatively large size of the crystals supports this observation: the rate of cooling within a furnace would be very rapid compared to the cooling rate of the igneous melt from which the crystals originally formed, and rapid recrystallization would produce very small crystals.

However, the vitrified appearance of the areas of the bulk sample beneath the slag layer does suggest that some melting took place. It may thus be suggested that partial melting of some or all types of crystal occurred. This causes the edges of the crystals to appear more rounded and for melt channels to appear around their periphery. Unfortunately, scanning electron micrography does not show these features clearly. To confirm partial melting the samples should be examined in thin section using transmitted light microscopy.

Of the minerals commonly found in granite, biotite and feldspar have variable compositions and therefore have no fixed melting point. Different sources give widely different melting ranges for these minerals. Sodium feldspar is usually considered to melt around 1170-1200°C; potassium feldspar melts around 1250°C; minerals in the mica group (which includes biotite) start melting above 1250°C. The melting point of quartz is in excess of 1600°C, although in mixed mineral melts in geological settings it can melt at a temperature as low as 700°C.

Considering these mineral melting ranges generally, it is probable that typical temperatures in a blowing house furnace, which are unlikely to exceed 1200°C, are just sufficient to permit partial melting of a thin layer of rock closest to the heat source. The vitrification zone is typically 2 to 3 cm thick. An experiment by the author to determine the melting behaviour of granite from Crift Farm in Cornwall demonstrated that after 30 minutes in an electric furnace at 1200°C a sample with a mass of a few grams melted sufficiently to adhere to the sides of a clay-graphite crucible and that the original pinkish colour of the granite was lost; after heating the sample was speckled black and white/clear.

Beyond the vitrification layer is a layer in which the granite has become very friable. In the aforementioned experiment, a sample of granite heated to 1000°C for 30 minutes retained its pinkish colour but became very brittle, such that the crystals could be flaked away manually. It may therefore be suggested that deeper within the furnace wall where temperatures are lower, conditions are such that some minerals are decomposing, but most remain unaltered.

The friable nature of the underlying granite would have facilitated the chipping away of the slagged region. The cleaned block would be some 5-10 cm thinner than previously, and so this process could not have gone on indefinitely. The granite blocks would eventually have required replacing, but once cleaned could have been used for other purposes requiring a shaped block, which might go some way to explaining why so few furnace blocks are found at blowing house sites.

It is not clear from the samples examined why the inner surface of the furnace required chipping away. Despite the friable layer, the vitrified layer would probably prevent pieces of granite dropping off into the furnace, and the slag layer on these specimens is

very thin and unlikely to be problematic. However, it is possible that towards the base of the furnace a thicker layer of slag could have adhered to the furnace wall, which it was necessary to remove to prevent clogging of the furnace. Once removed, the furnace wall material with the thick slag layer may have been put through the stamps for crushing such that the slag could be re-cycled to the furnace, or prills recovered from it. The samples found at Upper Merrivale may represent the few fragments that were discarded because the slag layer was too thin for crushing to be considered worthwhile. If this is so, then the samples of furnace lining cannot be considered representative of the damage to the furnace caused by smelting.

Despite the evidence for a clay lining in the furnace excavated at Upper Merrivale (see p136), visual examination of the furnace wall samples from this site revealed no sign of it: slag adheres directly onto granite.

Detection of any residual clay lining using scanning electron microscopy is problematical in that fire clays are alumino-silicates, and thus have the same general composition as granite. It would be expected that local clays, formed by the decomposition of feldspars and biotite that occur in the granite, would not be distinguishable by this method. However, as some clay minerals (the smectite group) contain calcium, and the Upper Merrivale granite contains only traces of this element, the possibility arises that if the clay were brought in from elsewhere it might be sufficiently dissimilar in composition to the granite to allow its presence to be detected. X-ray maps of calcium distribution were generated to try to detect clay layers in the Upper Merrivale samples. However, no increase in the levels of calcium between the outer slagged face of the sample and the slag/granite interface were observed, and owing to the fact that the calcium $K_{\alpha 1}$ X-ray peak coincides with the tin $L_{\beta 1}$ peak, it is

probable that the distribution of calcium is masked by the high levels of tin present in the area under examination.

Fully quantitative analysis of Sample UMF02 showed that the slag layer contained only 0.3% CaO, which is equal to the amounts present in the feldspar crystals in the granite, and is at the lower end of the range of 0.3% to 1% seen in the ordinary slag samples from this site (see Table 3.2, p244). This suggests that calcium in the slag derives from the fuel ash and that the low levels of calcium seen in the glassy slag layer in the furnace wall material sample are a result of dilution by elements from the granite.

The failure to confirm the presence of a clay lining may be interpreted in two ways. The interior of the furnace may originally have been entirely coated in a layer of clay, but as acid slags react readily with refractories such as clay (and also granite), any lining might be wholly absorbed into the slag, at which point, clay having a very similar chemical composition to granite, it would become impossible to determine whether the original material was clay or granite. Alternatively, it is possible that the furnace consisted of granite blocks with clay only used to seal the gaps between them, and that in the samples examined molten slag was in direct contact with the granite.

The one sample of clay that has had its chemical composition determined is of no assistance in this matter. The material from Godolphin (SW60323205) is in appearance altogether different from the samples of blowing house furnace linings. That a burning house stood on the site is historically documented (CRO RH 210), and the fact that the coating on the sample is rich in arsenic, and is associated with lesser quantities of other economically important minerals, including tin, is what would be expected if the clay had made up part of a rabbling bed in a burning house, heat-treating arsenical and sulphur-rich tin ores prior to smelting.

Given that the majority of furnace lining samples contain mineral crystals that have been subjected to a high temperature event, these should, in theory, be suitable candidates for thermoluminescence dating. However, concerns have been raised about the use of this technique on strongly heated materials, including archaeometallurgical remains, higher temperatures apparently causing the determined age of samples to be younger than their true age (Kresten et al 2003). It would be necessary to know the working temperature of the furnace from which samples of furnace linings derived in order to compensate for this effect.

4.4: Metallic Tin

Examples of metallic tin that can be attributed to specific blowing houses are not common in the archaeological record, so the pieces from Upper Merrivale and Trevellas Porth are of particular interest because they can provide direct evidence for the purity of metal being produced at that site, whereas ordinarily this must be surmised from prills trapped in the slag (for the difficulties associated with this see p406). Even so, it is necessary to bear in mind that the quality of metal will change through the course of a smelt and that each separate batch of ore will potentially produce more or less inferior metal.

The irregular lumps of oxidised tin recovered from beneath the furnace at Upper Merrivale illustrate very nicely one of the difficulties faced by the smelters: that molten tin is extremely fluid and will escape through the slightest crack in the furnace wall. It is unusual to find tin beneath an undisturbed furnace; probably furnaces were dismantled to recover any lost tin, which was valuable, once a blowing house went out of use (Barton 1968 p135).

Although, under normal circumstances, tin corrodes only very slowly, the tin from Upper Merrivale, which must be assumed to have deposited beneath the furnace some time in the 17th Century, is covered with a powdery cream-white layer that analysis indicated was a mixture of cassiterite (SnO_2) and romarchite (SnO). It may be, therefore, that the burial environment provided the right conditions to promote oxidation. It has been shown that at temperatures over 100°C, a slow but observable reaction between tin and oxygen occurs (Mantell 1949 p476). During smelting, heat radiating from the furnace may have raised the temperature of the ground beneath such

that over a relatively long period of time corrosion of the metallic tin proceeded at a faster pace than might otherwise be expected.

Chemicals from the burial environment appear to have migrated into the outer layers of the Upper Merrivale tin samples, as suggested by the presence of silicon, aluminium and iron in the ICPMS results (see Table 3.30, p368), however the inner portion of the largest sample (4/32) is apparently less affected, though the metal has a lamellar appearance indicating that some corrosion has occurred even there. Analysis suggests that the bulk of the interior is relatively pure tin metal, with only traces of metallic elements such as copper, arsenic and antimony. These metallic elements are more easily reduced than tin (see p412). The absence of iron in the central portion of the sample suggests that, at least on the occasion that this small quantity of metal escaped the furnace, conditions in the furnace were mildly reducing, so that iron oxides were not being co-reduced from the ore, with the result that the metal produced was free from hardhead and of good quality. When comparing the purity of metal trapped as prills in slag samples from Upper Merrivale, it can be seen that the majority are of similar high quality to the escaped tin sample.

It is more difficult to be certain of the source of the samples from Trevellas Porth, the second site to have yielded fragments of tin metal, on account of their being scattered surface finds. It is possible that they are pieces of tin that escaped through the base of the furnace, which were only rediscovered long after its removal, when the ground surface was eroded. Alternatively, they could have been produced during the refining process, being droplets of impure metal that were left behind in the bottom of the float when the tin was ladled out into the mould.

Although of roughly the same age as the Upper Merrivale samples, they are considerably less corroded, which may mean that the samples were not subjected to the kind of conditions that would enhance oxidation; perhaps, for example, they did not spend a protracted time beneath the furnace. Though their surfaces are dulled from a coating of oxide (the dark colour probably indicating the majority of the oxide being present as romarchite (SnO)), the samples still have a recognizably metallic appearance, and sectioning reveals uncorroded metal, present as shiny flakes, embedded within. The presence in the central portions of the sample of other metallic and non-metallic elements at levels of a few percent may be impurities in the tin metal and traces of slag and fuel ash, but it is not possible to rule out contamination from the burial environment. Assuming the former, the sample appears to be composed of discrete areas of metal of different composition, such that they appear as dark and light flakes. The dark flakes are tin accompanied by a few percent (<3%) copper, arsenic, antimony and molybdenum, while the light flakes have only traces (<0.3%) of impurities such as tungsten and molybdenum. Within any particular light flake, darker 'pocks' are visible at higher magnifications, which, although analysis was not possible owing to their small size, are almost certainly areas of contaminant metallic elements distributed within a matrix of relatively clean tin metal.

The purity of the prills in the Trevellas Porth slag was comparable to that of the light flakes in the metallic tin sample, i.e. arsenic, iron and molybdenum were present at trace levels.

Given the relatively good quality of the tin in the sample, interpreting it as escaped furnace metal seems a more likely prospect than it being discarded waste from refining.

In the case of the other, earlier metallic tin samples, no analysis of the metal was possible owing to the poor state of preservation of the specimens. Indeed, the very identification of tin metal in the archaeological record can be somewhat problematical, as noted in Section 3.4.4, for when tin corrodes it is oxidized to SnO (romarchite) and SnO_2 (cassiterite) and thus it has a very similar chemical composition as partially reduced ores.

Sample 4/29 from Carloggas serves to illustrate this difficulty, for the overall composition of the sample provides no real indication of its nature. However, the unusually flat edges of the sample seem unlikely to be natural, and may have resulted when molten metal solidified against a flat surface. Moreover, based on the analysis of the few examples of tin ore discovered at archaeological sites, there should be residual crystals of quartz, feldspar and possibly zircon present throughout the sample if it is partially reduced cassiterite, while these would not be present in an oxidized ingot, at least in the central portions that are unaffected by the burial environment. As no such inclusions were observed, it supports the assertion that the material from Carloggas is highly corroded tin metal.

Bearing in mind the probable contamination by the burial environment of the outer corrosion layers of the Upper Merrivale samples, great care should be exercised when using compositional data obtained from equally oxidised samples to draw conclusions regarding the purity of the original metal.

The main impurities that affect the quality of tin metal are iron, copper, arsenic, antimony, lead and bismuth; the majority of these causing the tin to become brittle, and impairing its lustre (Louis 1911 p6).

It is iron that causes the greatest difficulty, owing to the very similar conditions required for reduction of iron and tin (see p394). When tin is smelted in the presence of iron, the tin produced is physically mixed with areas of crystalline or granular intermetallic tin-iron compound, known as hardhead, which appear as greyish masses within the silvery bright tin (see Figure 3.43, p308).

The binary phase diagram for the tin-iron system (Appendix 12) indicates that several alloys of tin and iron are possible. The alloy most commonly formed during tin smelting is $FeSn_2$ (consisting of 19% Fe, 81% Sn), but FeSn, Fe_4Sn, Fe_5Sn, $FeSn_6$ and $FeSn_7$ are also possible. The fact that tin is allowed to cool to just above the freezing point before being cast into moulds (Thibault 1908 p210; Louis 1911 p25) would give sufficient time for crystal structures to alter.

That hardhead was a problem for the smelters in the blowing houses can be inferred from the writing of Beare (1586 p32), who makes reference to the grade of tin known as Hard Tin (although Smith (1996 p96) suggests that this may refer to tin contaminated with arsenic or copper), and is more clearly stated by the Inquisitive Person (Anon 1670), who describes an iron-rich material which he calls 'Mount Egge' found in the bottom of the float (see p423). As the most common variety of hardhead has a density of 7.74 g/cm^3, compared to 7.28 g/cm^3 for tin, the hardhead would sink to the bottom of the float as the molten metal was allowed to rest there. Leifchild (1855 p210) notes that 'The melted tin runs off from the furnace into an open basin, whence it runs into a large vessel, where it is allowed to settle. The scoriae are skimmed off; and subsequent operations consist of refining, by allowing the mass of the metal to rest, then submitting the upper and pure portion to the refining basin, and remelting the lower part.'

Agricola (1556 p418) states that 'poor quality tin metal, which cracked when struck with a hammer, was formed into cakes… and these cakes were melted on an open hearth constructed out of sandstone blocks arranged in a V-shape, and dipping towards one end so that the molten tin would run down the centre into a dipping pot placed to catch it. Five or six cakes of tin were placed upon logs of wood, arranged within the hearth. The impure tin sank to the bottom of the pot; the pure tin floated on top of it, and could be ladled out to make a lattice bar. The impure tin was again made into cakes. The quality of the tin could be determined by the ease of flow.'

It thus appears that, in Germany at least, some subsequent refining of the impure metal took place. Unfortunately, there is no description of English tin being similarly treated in this period.

The production of a certain quantity of hardhead was an accepted part of smelting from the 18th Century, and methods of dealing with it were well established (see p179-82). The process of liquation relies on the fact that tin has a melting point of only 232°C and is thus extremely fluid when furnaced, whereas the temperature at which the various tin-iron compounds melt is 1130°C (see phase diagram in Appendix 12)

In addition to Hard Tin, Beare also notes the existence of a grade of tin known as 'Relistian Tin'. Relistian (SW606367) was a tin and copper mine possessing a complex mineralogy (Hamilton-Jenkin 1963 p30-8); workers at the Newham smelting works at the beginning of the 18th Century referred to 'Relistian oar being of mundick nature' (Barton 1971 p88).

It is possible that the tinners in Beare's time were unable to deal effectively with this type of vein ore, and Relistian mine must have produced enough 'corrupt' tin to cause its name to become equated - even in distant Blackmore Stannary, and presumably

throughout Cornwall - with a poor grade of tin. There is no record of the nature of Relistian tin, but based on what information is available regarding the ore from the mine of that name it might be supposed that it contained copper, iron and possibly other contaminants including arsenic.

Louis (1911 p8) reports that arsenic has been detected in combination with hardhead deriving from the smelting of impure ores or slag re-smelting, relative proportions being roughly 18% Sn, 22% As and 53% Fe. Figures obtained by Pearce (1871), who analysed specimens of hardhead obtained from several unspecified locations around Cornwall, were in close agreement with this (16% Sn, 18% As, 54% Fe), and led him to suggest that 'the presence of iron… may be somewhat beneficial in the smelting of tin ores which contains much arsenic, as they form fusible compounds with the arsenic which otherwise would alloy with the tin and deteriorate its quantity'. Certainly, the percentage of tin found in these arsenical hardheads is about one quarter of that found in the usual tin-iron alloy $FeSn_2$. However, in reverberatory smelting hardhead was normally added to a later furnace charge, but it may not have been considered desirable to treat arsenical hardheads this way and contaminate the charge with more arsenic, thus this metal may have been discarded with a concomitant loss of tin from the system.

No hardhead of the above composition was detected either in samples of metal or in prills trapped in slag that were analysed in this work. Arsenic was present only in some of the individual phases in prills from Trereife slag sample 3/35 (See Table 3.10, p299).

It is likely that many of the vein ores being exploited in the Post-Mediaeval period contained problematical minerals, which gave rise to the popular belief that lode ore was inferior to stream tin, e.g. Carew (1602 p29). However, it is not always the case that alluvial cassiterite is 'pure' (see Section 1.3.3), and moreover, as the documentary

record implies that cassiterite from different sources was smelted separately (e.g. Beare 1586 p107), a blower would no doubt recognize the truth regarding the various types of ores available in his locality.

The fact that the increasing use of vein ores coincided with a trend towards bigger furnaces and bigger bellows would have exacerbated the problem of corrupt tin, for an intensification of the blast strength would result in impurities being co-smelted with the cassiterite.

It is not possible to remove low melting point elements such as lead (327°C) and bismuth (271°C) from smelted tin by liquation. These were removed by boiling and tossing (Louis 1911 p24). Neither element appears to have been present above trace levels in the slags analysed; being easily reduced it partitions into the metal. Lead levels of more than 3000 ppm were detected using ICPMS in areas of the tin metal from Trevellas Porth blowing house.

It has been noted (p140) that some of the mouldstones associated with blowing houses have one or more small cavities beside the main mould. There is no evidence from documentary sources relating to the function of these small moulds, and their purpose has been considered by several researchers. Greeves (1981a) suggested that a small ingot might have been used as payment to the Stannary bailiffs of the tax known as White Rent. Others, including Greeves (1981a,b), Gerrard (1986 p151) and Earl (1991) have raised the possibility that these small moulds were used for illicit purposes: producing ‘pocket tin’ that was easy to transport and conceal, thus facilitating smuggling. Gerrard (1986 p151) went on to propose that mouldstones with sample moulds must date from the period before 1660 when blowing house supervisors, whose role it was to clamp down on attempts to avoid coinage duty, were appointed (Lewis

1908 p155, Barton 1971 p62), with the result that blowers who had openly cast small ingots would no longer be able to do so once their houses were subject to regular inspections by these officials. However, even a casual examination of Devon's mouldstones shows that sample moulds are associated with main mould cavities of all sizes, including moulds with relatively large capacities that might be assumed to be of late date. The in situ mould in the blowing house at Upper Merrivale, believed to have been abandoned some time around AD 1700 (Greeves 1994) has sample moulds, as did the extremely large mouldstone (now missing) from Longstone, a blowing house that may have been operating as late as the 1740s. Any explanation of the use of sample moulds should take this into account.

Thus the possibility must be considered that the sample moulds are just that: moulds used for sampling the molten tin to assess its purity and readiness for casting. The fact that blowers marked any substandard tin with the letter H (e.g. Beare 1556 p32; Carew 1602 p27) before it left the blowing house to be presented for coinage means that its quality must have been assessed in some manner at the blowing house. Rather than relying solely on the appearance and fluidity of the tin in the float, a blower may have carried out physical tests on a small sample of the tin, as was the practice in the 19th Century. Thibault (1908 p210) describes the testing of tin from a reverberatory furnace thus: 'One method employed by the refiner to determine the quality of the tin is to take a small ladleful and after having cleaned it by stirring and skimming, cast it into a small ingot mould, and as it cools he closely observes its appearance. If it remains bright and clean, and full and rounded on the sides until quite cold, it is sufficiently pure to be classified as grain tin. If however the ingot though bright, should not remain so full and rounded at the sides, and if at the moment of solidification, a frosted crystalline appearance shoots from the centre out to the sides, the tin is classed as second grade, or

block tin. Should the metal assume a slight yellowish appearance, and crystalline stria appear much sooner, covering the whole of the surface it is an indication that it is unfit for market, and therefore must be further purified by liquation etc.'

4.5: The Interpretation of Early Smelting Remains

Examination of the few pieces of slag that appear to date from before A.D. 1000 offer some clues regarding early tin production. The slags from Caerloggas, Upper Merrivale (sample 2/25) and Whitten Knowles have compositions that suggest that they would melt at relatively low temperatures, and experimental re-melting of a small piece of the Caerloggas slag by Salter (1997) confirmed that this slag began to melt at 1050°C. Taken in conjunction with the observation that experimentally reheated slag from Crift Farm, which has a not dissimilar composition, began melting at 1000°C (see p313), it can be suggested that all the early slag samples would be fluid below 1100°C, although highly viscous as the morphology of the samples suggests.

The seven fragments of slag from Caerloggas and most of the 30 or so fragments from Whitten Knowles (Figure 4.8) appear to have formed a thin layer, probably whilst overlying molten tin. The ribbon-like morphology of the pieces indicates that the slag also flowed. Flow structures could arise as a result of smelting being carried out in tapped shaft furnaces, but the possibility that they were generated when the slag was scraped off the surface of the metal in a pit furnace cannot be rejected.

One of the characteristic features of this group of slags is a very high tin content. The Caerloggas samples were found to contain 37.5 and 44.5% SnO; the Whitten Knowles slag had 29.6% SnO and the Upper Merrivale sample 37.5% SnO. In addition, all these samples contained metallic prills. By later standards, this would have been considered an unacceptable loss of tin; however, if the amount of slag generated is very small, losses are minimized.

Figure 4.8: Slag from Whitten Knowles.

In the calculation on p390 for a model slag containing 40% SnO, the mass of slag generated was estimated at 292g for a tin yield of 539g. Although it is quite difficult to date most archaeological tin ingots, all of the ingots believed to be pre-Mediaeval are relatively small. Their exact size varies, but they typically have masses in the range of 0.5 to 15 kg (see Catalogue of Tin Metal Finds). Therefore, assuming production of a 10 kg ingot, the above figures mean that 5.4 kg of slag would be generated. If the purity of the ore used is higher, however, the amount of slag generated falls dramatically; for example, ore with a tin content of 70% would produce only 2.9 kg of slag per 10 kg of metal; pure cassiterite containing 79% Sn would produce no slag. High quality ores would have been available to early smelters: analysis of the stream tin pebbles from Caerloggas and Dean Moor (see p316) show SnO_2 present at between 60 and 67% (equating to 47% and 53% Sn) even before crushing and washing. It does not appear, however, that gangue minerals were completely eradicated from the ore concentrates used by early smelters: all the early slags examined contain sub-millimetre sized residual mineral crystals.

The high tin content observed suggests slag recycling was not a feature of the early smelting process.

Given the striking rarity of prehistoric tin slag, it might be suggested that slagging furnaces were not a common feature of early smelting, although descriptions of smelting in manually-blown pit furnaces carried out in relatively modern times in various parts of the world imply that slag production is quite feasible with this technology. Pit furnaces in Borneo, blown by a cylinder piston built out of a tree trunk, produced tin metal and slag with 15% SnO_2 and prills (Thibault 1908 p167-9), and Gowland (1899) noted that slag was raked off the surface of the molten metal formed in pit furnaces operating in Japan in 1883, which used two hand-powered bellows to deliver the draught to the edge of the cavity.

However, both bowl furnaces and bellows-blown shaft furnaces constructed by researchers investigating the practicalities of prehistoric tin smelting (Timberlake 1994; Earl 1986) have produced tin with little or no hard glassy slag being generated.

An experimental bowl furnace constructed by Timberlake produced droplets of unconsolidated metal that were collected from amongst a residue of ashes and powdery unreduced cassiterite once smelting was complete. Only small quantities of slag were produced in Earl's shaft furnaces. Again, partially reduced cassiterite and much friable cindery material were reported.

As the main role of slag is to remove impurities from the ore during smelting, a furnace utilizing very clean ores could perhaps produce a similar yield to a slagging furnace, without the disadvantage of tin chemically combining with the slag and being lost (Grant 1994). Reduction of tin without producing a slag also has the advantage of reducing the amount of fuel required: slag formation is an endothermic reaction, so the

greater the volume of slag generated, the more energy needs to be input into the system (Moore 1990 p152). In the absence of slag formation, unfused gangue minerals and unreduced cassiterite would remain within the furnace as a powdery sintered matrix.

An experienced smelter would have been able to operate the furnace to optimize the yield of tin, so whether early furnaces produced slag or not is likely to have depended upon the quality of the ores used. The nature of the archaeological remains of the earliest furnaces, then, might be expected to show variation with regard to the local geology. It is probable that slagging furnaces became the norm relatively quickly as the demand for ore expanded, although the amounts of slag produced were probably small.

In addition to the slag itself, the metallic prills trapped within it may be informative.

The blast for furnaces in the prehistoric period, whether of pit or shaft types, would almost certainly have been generated by some manner of hand-powered bellows, the design of which is unlikely ever to be known; a simple bag bellows would have been sufficient, though over time bellows design may have become more sophisticated. The important point to note is that the draught generated would have been relatively mild; reducing conditions within the furnace would thus be gentle, which theoretically would promote the formation of clean tin metal, there being less chance of iron being co-reduced from the ore with the tin.

The fact that prills trapped in the slag from Caerloggas are tin with only trace levels of impurities, and similarly that prills in slags from other sites of possible early date (Upper Merrivale (sample 2/25), Yes Tor Bottom and Metherel) are also high quality tin, is consistent with the idea that gentle reducing conditions prevailed during smelting.

That said, the results of experimental smelting highlight the need for very clean ores: the metal produced in Timberlake's bowl furnace (Timberlake 1994) from a 60-65% SnO_2 concentrate of stream tin, occurred as unconsolidated droplets of variable quality. Although some were shown to be 99% pure tin, analysis by the present author demonstrated that others were contaminated with iron and arsenic, elements which had been identified by the experimenter as contaminants in the ore; these droplets were noticeably duller and had a knobbly morphology (see Figure 4.9).

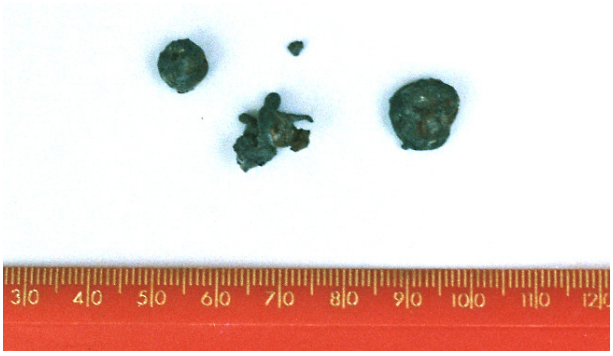


Figure 4.9: Prills of metal from an experimental smelt by Timberlake; the irregular central prill is impure tin.

The purity of prills in early slags also suggests that the ingots produced at these sites were relatively pure and it is probable that refining of the metal prior to the ingot being cast was unnecessary. (The caveat that smelted tin and prills could have different compositions is discussed on p406). Analysis of ingots of probable early date (e.g. Carnanton, Praa Sands) has previously shown that these contain few impurities. To dismiss the methods of smelting used in this period as 'primitive' would thus be misleading, suggesting something that is in some way substandard. The technology may have been relatively simple, but it is worth stressing that it is an effective technology.

It cannot, however, be considered an efficient technology. Quite apart from the high loss of tin to the slag, as a consequence of the relatively low temperatures at which these furnaces probably operated, rates of reaction would have been low; fuel consumption per unit of tin produced would thus be relatively high.

4.6: Pre-Blowing House Smelting in the Mediaeval Period

4.6.1: Case Study: The Interpretation of Crift Farm as a Smelting Site

The excavations at Crift Farm (SX067602) near Lanlivery offered a rare opportunity to examine a site with tin smelting remains that apparently worked at a time just prior to the introduction of water-powered blowing house blast furnaces (see p94-9).

This Early Mediaeval site has raised several questions. Was the smelting carried out at the excavated longhouse, or was the slag brought there either for secondary processing or for hardcore? What processes and techniques were used to produce the tin? What role did tin - and the presence of the smelting site at Crift - play in the local economy?

It is probable that tin smelting was carried out somewhere in the vicinity of Crift Farm, which is situated on the west-facing flank of Crift Down, approximately 6 km south of Bodmin and 4 km west-northwest of Lostwithiel. Crift Downs is a spur of high ground surrounded on its west, north and east flanks by some of the largest alluvial tin deposits in Europe. At Red Moor, a marshy area on the eastern side of the Downs, only a kilometre to the north of Crift Farm, alluvial cassiterite lies at a shallower level than elsewhere in the county (between 2 and 8 metres below the peat and gravel overburden) and was still being dug by traditional methods in the first decade of the 20th Century (Embrey and Symes 1987 p16), and, as mentioned previously (p89), work on peat from the lowlands to the southwest of the Crift Farm site show elevated levels of tin between AD 895 and 1155, suggesting exploitation of these ores (West et al 1997). Exactly where in relation to the ore source smelting was carried out remains a matter of debate, but given the proximity of the Crift Farm longhouse to the alluvial deposits, there

would have been little difficulty in transporting ore to this site. Though no ore dump was located during the investigations of the site, it would have provided a secure place to store washed ore until a sufficient quantity was obtained to fill the furnace.

The only cassiterite found was a single fragment recovered from the spoil heap. Its appearance is not typical of alluvial ore. The angularity of this sample suggests that it could be a piece of mined vein ore, eluvial 'shoad', or part of a larger alluvial pebble that has already been subjected to preliminary processing. The stone hammers found at the site could have been used for this purpose, as could the crazing stone.

Excavation did reveal unequivocal evidence for high temperature metal working within the main part of the building (Building A). Initial investigations by Buckley and Earl (1990) located a stone lined 'bosh' or quenching trough containing iron smithing hammerscale, and close by a small iron smithing hearth-bottom, similar to a previously discovered surface find. A knowledge of metal working by the occupants of the building and the fact of their willingness to use the main building to carry out such procedures is thus not in doubt, but all of the remains relating to high-temperature processes were connected to iron smithing, not to tin smelting. The radiocarbon dating of the site to AD 1020-1270 at 2σ (Hedges et al 1992) is also based upon charcoal samples associated with the iron working remains.

So was this building also used for smelting tin?

Although the earliest phase of building, Building A, was poorly preserved, it appears that concentrations of slag, several fine-grained granite hammer stones and two pieces of crazing stone had been incorporated into the walls. The earliest tin ore processing and/or smelting on site must therefore either pre-date construction of Building A, or be

contemporary with it if the damaged tools and slag were included in the cob during renovation.

The one piece of evidence that could have proven beyond question that smelting was carried out on site is lacking. Despite Buckley and Earl's initial assertion that they had identified a hearth, no furnace structure, or any part thereof, has been found, but this is not unusual: very few smelting sites of any date have remains recognizable as furnaces.

One intriguing surface find from the University of Bradford excavations was a ceramic tube, which could have been used as a tuyère for a bellows. There was no slag adhering to the tube, however, to confirm this identification, and it has since been considered that it might be part of a jug handle.

The most potent argument in favour of tin smelting having taken place in the Crift Farm longhouse is simply the presence of such a large quantity of tin slag – McDonnell estimates approximately one tonne of slag dumped against the side of Building A (McDonnell 1993), and that this was deposited in discrete lenses suggests that material was added to the dump episodically over a period of time (see p478). In view of this, and the fact that no other similar slag deposits were uncovered on the site (all other slag finds were thinly scattered individual pieces) it seems unlikely that the slag was brought to the site for use as hardcore. The presence of stone implements on site also supports this assertion. Although stone hammers are portable, crazing stones are heavy and considerably less so, which implies some manner of tin-working on site.

This then raises the question of what use the Crift Farm crazing stone was put to. Buckley and Earl (1990) report that the striations on the inner face of the crazing stone contained finely crushed tin slag, although no information is given regarding the analysis of this material. This leads them to state that the evidence 'backs the idea of re-

treatment of tin slag for the 20% tin in it', though they do not dismiss the possibility of primary smelting of ore. Documentary sources (though all dating from after the introduction of stamps for ore processing) state that crazing stones were used for grinding certain types of ore (Carew 1602 p24; Anon 1670). There are no contemporary references to slag being crushed using a crazing mill prior to its being returned to the furnace, although there is no reason why this could not have occurred. The presence of a crazing stone does not, therefore, shed any light on whether primary or secondary processing was being carried out at Crift Farm. Currently, there is no sign that the slag in the dump has been treated in any way in order to recover the tin trapped within it. Analysis of micro-residues from the floor of the building or the contemporary ground surface outside it might resolve the issue: cassiterite deposits (with or without crushed slag fragments, since slag may be recycled) giving support to primary smelting, with crushed slag alone being indicative of reprocessing.

On the question of slag re-processing, there are three possible ways to recover tin from slag: by mechanically crushing it and recovering prills; by melting it to allow metal from prills to separate out under the influence of gravity; otherwise, the slag must be returned to the furnace and re-smelted at a higher temperature, in an attempt to recover tin both in the form of prills and chemically combined as silicate.

Given that analysis shows the quality of the metal in prills in the Crift Farm slag is good, recovery of prills by crushing would have been a viable process. As the majority of the prills are extremely small, rarely exceeding 1mm, hand-picking of large prills after crushing would be impractical. Hydraulic separation of the denser metal would be necessary. Deposits of crushed slag would indicate that this procedure had been carried out, but none were noted during excavation of the site. The lack of running water on the

site does not necessarily rule out hydraulic separation, as it is possible to carry out this process using a small amount of water in a basin or on the bed of a shovel (S. Polglase pers comm.). The recovery of tin from slag by this method seems unlikely to have happened simply based on the amount of unprocessed slag that has been left dumped at the site.

The process of recovering metallic prills by melting slag is described by Thibault (1908 p222): '…the greater the specific gravity of the metal, as compared with the slag, is relied upon for the purpose of separating it; but as the slag, which consists mainly of ferrous and stannous silicates, is relatively heavy, and tin is only a light metal, much difficulty is always experienced in effecting a good separation. Consequently much of the metal remains with the slag…'

The very high viscosity of the Crift Farm slag would compound the problem caused by the small difference in the densities of the slag and metal. This method is thus unlikely to have been effective if applied to the Crift Farm slags.

Whether tin was obtained by re-smelting slag is a more difficult question to address. The fact that the slag dumped at Crift Farm has been shown to have a fairly consistent composition (Tylecote et al 1989; Adriaens 1996; Aylett 1996 p38-45; Malham 1996 p56-8, 2002, 2003, and also see Table 3.2, p244) suggests that all the material was treated similarly, but whether it is the product of primary ore smelting or the product of slag reprocessing is not known. The quality of the metal in the prills suggests the former: metal produced as a result of slag processing tends to contain a high proportion of iron, and this is notably absent in the Crift Farm prills.

It must also be considered whether re-smelting was technically and economically feasible, given that the temperature required for re-smelting is much higher than that for

ore smelting (Thibault 1908 p6). The temperature obtainable in a hand-blown furnace may not have been sufficiently high to reduce much tin from the slag. (Considering the very high viscosity of the Crift Farm slags (see Section 3.1.5) the problem of residence time in the furnace is unlikely to have been an issue: some re-melted slags can pass through the furnace very quickly, particularly if the shaft-size is small, and pass out of the furnace having reached a temperature not much higher than their melting point (Smith 1996)). The re-smelting operation would consume charcoal, so the output of tin would have to be great enough to offset the cost of the extra fuel. Running the furnace would require men to work the bellows, so the yield of tin would have to be balanced against their effort, particularly with a rich source of fresh ore available close by that potentially offered a greater reward in terms of tin output in relation to the amount of work it took to produce that tin. The metal produced by reprocessing slags would have been tin contaminated with hardhead, requiring additional refining, which would be more work and incur more fuel costs.

If it is accepted that primary smelting of tin ores was carried out at Crift Farm, certain conclusions can be drawn regarding the process and technology used.

In the absence of any archaeological remains, the appearance of the furnace can only be speculated upon. The early date of the site in relation to the generally accepted date for the introduction of water-powered blowing houses, and its position relative to water sources suitable for powering bellows, make it certain that the furnace draught was supplied by some manner of hand-powered bellows. The presence of substantial fragments of vitrified and slagged granite in the slag heap indicates a structure formed of granite blocks, suggesting a shaft furnace rather than a pit furnace. Examination of said fragments by Aylett (1996) and the present author reveal no sign of clay lining; if

such a lining was present it must have been totally absorbed into the slag during smelting, and the slag has reacted with the granite beneath.

No meaningful estimate of the furnace's dimensions can be made, but the fact that it was hand-blown means that it was probably smaller than the later blowing house furnaces (see p134).

Descriptions of blowing house furnaces, and shaft blast furnaces in other parts of the world, all indicate that shaft furnaces for tin smelting operated with an open taphole, beyond which was some manner of cavity to collect the tin flowing out of the furnace. It is unlikely that the Crift Farm furnace differed in any great respect from this basic design. The rod-like morphology of many of the slag samples hints at the movement of slag out of the furnace, and the crescent-shape of some pieces may have been produced when the molten slag was skimmed off the molten metal (see p221).

The operating temperature of the furnace cannot be established with any certainty, but based on the results of the experimental re-melting of the Crift Farm slags (see Section 3.1.5) a minimum temperature of 1000°C can be postulated, below which the slag would not be molten. Temperatures may have reached at least 1100°C.

The high tin residual tin content in the Crift Farm slag means that when molten it has a high viscosity, as both the morphology of the slag samples and experimental re-melting attests. Raising the temperature in the furnace would not cause the slag to become markedly more fluid, so would not greatly improve slag metal separation. However, a higher temperature would increase reaction rates, thus increasing the amount of tin reduced, which is advantageous in terms of time and labour and also reduces the amount of fuel used per unit of tin produced. While a higher temperature, and the stronger draught required to produce that, increases the possibility of co-smelting of

iron oxides, the use of hand-powered bellows would limit the draught strength achievable, so provided the smelters were using relatively clean ores, co-reduction is unlikely to have been a major problem.

A very rough calculation can be made of the amount of tin metal produced at Crift Farm, based on the estimated 1 tonne of slag deposited at the site:

Approximate composition of slag = 20% SnO + 80% gangue elements.

$\therefore$ Total mass of gangue elements in slag in the dump = 80% x 1000 kg = 800 kg

and

Total mass of SnO in the dump = 20% x 1000 kg = 200 kg

but 20% SnO equates to 17.6% Sn metal:

(%SnO x RAM Sn) / RMM SnO = (20 x 119) / 135 = 17.6

$\therefore$ Total mass of Sn metal in dump = 17.6% x 1000 kg = 176 kg.

Assuming the ore used to produce the tin metal + slag is a concentrate consisting of 65% Sn (= 82% SnO_2), then the proportion of gangue elements in the ore = 18%.

Assuming the gangue elements in the slag derive wholly from the ore, then

18% gangue elements in ore $\Rightarrow$ 800 kg gangue elements in slag.

The original mass of the ore used can thus be calculated:

100% of ore mass = (800 x 100) / 18 = 4444 kg

As the ore concentrate = 65% Sn, the maximum yield from the ore = 65% x 4444 kg = 2888 kg.

Actual yield of tin metal = 100% yield – Sn lost to slag = 2888 – 176 = 2712 kg.

To put this into context, this equates to c.5% of the entire annual output for Devon and Cornwall in the mid 12th Century, which, estimated from the Pipe Rolls, was in the region of 55000 kg (see p76). This strongly suggests that the Crift Farm site operated over an extended period of time.

Thomas Beare's 16th Century account of smelting indicates that approximately 300 lbs (136 kg) of metallic tin were produced in 12 hours in a blowing house (Beare 1556 p107). Although no furnace remains at Crift Farm, it is not unreasonable to suggest that the furnace would have been somewhat smaller than those found in blowing houses, and thus the tin output would be correspondingly lower. Estimates of ingot sizes, based on the number of blocks presented for coinage and the total mass of tin coined, indicate that the mean weight of ingots increased from the Mediaeval and into the Post-mediaeval. In 1305 the mean ingot weight was 126 lbs (57kg); by 1577 it was 308 lbs (140kg) (Maclean 1874). From this, it appears that a single ingot was produced from each smelt. The ingots produced at Crift Farm may have been smaller, but if it is assumed that the furnace produced 50 kg of metallic tin per smelt, the 2700 kg output estimated from the size of the slag heap would equate to 54 smelts. There are no early documentary sources to suggest the frequency with which the Crift Farm furnace would have been used.

As for the quality of the tin being produced, it has already been noted (p476) that the relatively gentle reducing conditions that a small furnace with hand-powered bellows would have generated would have kept the co-reduction of iron oxides to a minimum.

However, other more easily reduced metallic elements could potentially enter the tin. Analysis of the cassiterite fragment found on the spoil heap during the excavation of the Crift Farm site showed it to be relatively rich, with 75% SnO_2 and only very minor fine-grained impurities, but as no other ores were recovered from the site, it is not known if the sample is representative of the ores generally used there. Such ore may or may not have been processed further. The cassiterite crystals in the sample were associated with small amounts of antimony, which could have been co-reduced with the tin (see p319), however analysis of metallic prills trapped in the slag suggests that the metal being produced was of high purity, and antimony was not a problem (see Table 3.10, p300).

4.6.2: The Crift Farm Smelting Site and its Place in the Cornish Economy

Although available production figures indicate that the majority of tin originated in Devon in the Early Mediaeval, some was produced in Cornwall (Lewis 1908 p252-8; Hatcher 1973 p154-9). These early records are silent about where in each county the production centres were located, but later documentation makes it clear that a large proportion of Cornish tin was coined in the eastern Stannary towns, one of which was Lostwithiel, the implication being that the alluvial cassiterite deposits in the local area were being exploited and that the production of tin made an important contribution to the economy of the area.

The extent to which tin production at Crift Farm contributed to the local economy is a difficult question to answer. Leaving aside the doubts regarding the identification of Crift Farm as a primary smelting site, there is still a problem determining how much tin was produced there annually, although a rough estimate of total output has been

attempted (see p477). It is not possible to determine the timescale over which the slagheap accumulated – and thus the time that smelting was carried out at the site. It may have been a small family concern that continued over many years, or it may have been a more substantial operation serving the tinners of the area for a much briefer period.

Either way, the Crift Farm longhouse was, in the Early Mediaeval period, well placed to access trade networks: the Saint's Way - an old trans-Cornwall route - runs north-south along the crest of the ridge above the site, towards Lostwithiel and the Fowey Estuary.

It is possible, given the location of the site within a field system, that mining and smelting were carried out in tandem with agriculture. A reference in 1426 to John Aunger, husbandman and blower (Lewis 1908 p17), supports the idea that the two activities were not incompatible. Herring (1996 p77) suggests that as alluvial mining was probably a seasonal activity, carried out in the summer months, which is the busiest time in the agricultural year, it would be the landless who worked as tinners, but this may only have applied to those obtaining the ore rather than smelting it.

Archaeological investigation does not offer any clues as to why the Crift Farm smelting site fell out of use, and there are, of course, many reasons why it may have done so. The very loose dating of the site also presents difficulties in this respect. It is possible that the technology was superseded by the introduction of furnaces with water-powered bellows, but more probably smelting ceased at the site before this development.

4.6.3: Early Mediaeval Smelting as a Two Stage Process: The De Wrotham Correspondence

The documentary evidence for smelting in the Mediaeval period is, as discussed in Section 1.4.5.1, somewhat limited, but the correspondence between William De Wrotham and Archbishop Hubert of Canterbury does shed some light upon the process. One of the main ideas to emerge from these documents is that tin was apparently produced as a two-stage process, with first and second 'smeltings', and as this has generated a deal of speculation regarding the nature of each stage, it is worth considering the text in light of the physical evidence for smelting from this period.

In the original Latin text the term 'funtura' is used with regard to both the first and second process, while those carrying out said processes are 'fusores'; these terms are commonly translated as 'founding/casting' and 'founders' respectively, but owing to the context, are in the case of De Wrotham's correspondence invariably translated as 'smelting' and 'smelters', thus giving rise to references to 'tin of the first smelting' or 'tin of the second smelting' (see p78). However, this choice of wording may be misleading. It is probable that the 'first smelting' was a true smelting, i.e. the reduction of cassiterite to produce metallic tin, while the 'second smelting' referred either to subsequent refining of the metal or re-casting of the metal into different-sized ingots for sale. As there is no separate word in Latin for smelting, no difficulty arises from the use of the word 'funtura' to describe two distinctly different processes, and although this failure to distinguish between processes may seem odd from a modern perspective, it is worth remembering that up until the 19th Century, tinners in the southwest of England referred to the reduction of cassiterite to tin metal in a blast furnace as 'melting' rather than 'smelting'.

The suggestion that the first smelting may have generated metal mixed with partially reduced cassiterite can be dismissed. Smelting residues from Crift Farm, a site that may be contemporary with the De Wrotham letter or earlier than it, indicate that furnace technology was sufficiently developed by this time to generate a fully glassy slag with entrained metallic prills. No deposits of powdery partially reduced cassiterite were found during the excavations of the site. Moreover, microanalysis of the slag showed no granular patches of tin oxide within the otherwise glassy slag matrix, such as have been observed in slag from crucible smelting experiments where full reduction did not appear to have occurred (see Figure 4.10, which shows slag from a crucible smelt of stream tin recovered from the River Dart below Buckfastleigh carried out by John-Walbeoffe-Wilson).

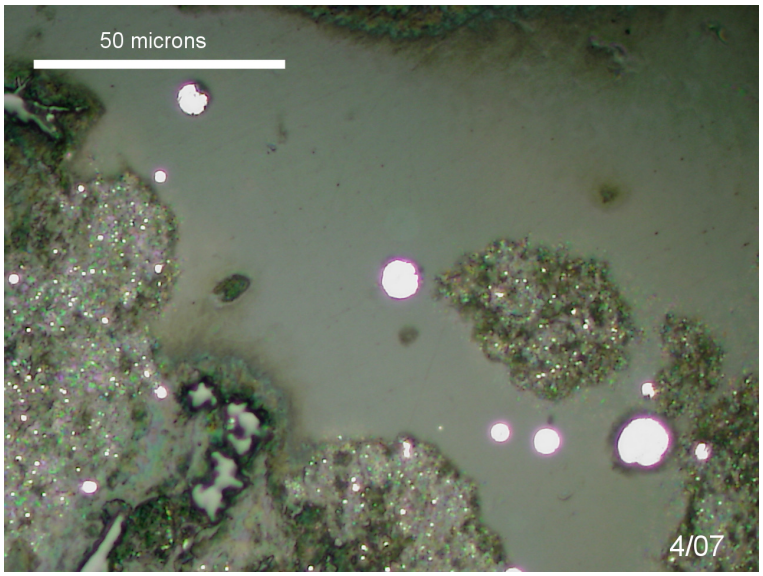


Figure 4.10: Slag from a crucible smelt showing glassy matrix containing large metallic prills, and granular patches of unreduced cassiterite intermingled with many very small prills.

That the end product of the first smelting was tin metal is clear from the wording of the restrictions relating to the ownership and trade of tin placed upon the tinners by De Wrotham: ‘No man nor woman…should presume to have within or outside the

stannaries any of the tin of the first smelting beyond a fortnight unless it be weighed and marked by the wardens and clerk of the weight and seal of the farm' (...non praesumat homo nec femina… in stannariis vel extra stannarias habere aliquid de stagno primae funturae ultra quindenam nisi sit ponderatum et signatum per custodes et clericum de pondere et cuneo firmae); 'No man nor woman… should presume to keep beyond thirteen weeks tin of the first smelting, weighed and stamped, unless it be put into the second smelting and the mark discharged' (…non praesumat homo nec femina… ultra tresdecim septimanas habere stagnum de prima funtura que signatum per pondus et cuneum primae funturae nisi sit positum in secundam funturam et acquitatum de marca) (translations from Worth 1910 & Halsall 1998). In order to be stamped with an impression (*signatum*) after the first smelting, the tin must have been in metallic form, and from 1198 the requirement was that this was done within 2 weeks of the tin being produced.

The tin of the first smelting was transported to an appointed place for the first stamp to be applied: No one was to 'buy or sell any tin of the first smelting, nor to give or carry away, outside the stannaries or *outside the places appointed for weighing and marking* the first smelting, until it shall have been weighed and marked… (…vendere vel emere aliquid de stagno primae funturae vel donare vel asportare nec extra stannarias nec extra loca ad ponderationem et signationem primae funturae constituta donee ponderetur et signetur...).

The tinners then had thirteen weeks to present their tin for the second smelting and second stamping. (It is perhaps significant that in later periods the coinages were held twice a year, at midsummer and Michaelmas (29th September), i.e. thirteen weeks apart). The second smelting was carried out in a market town: 'In any town, other than

the city of Exeter or the town of Bodmin, where there has been a second smelting, a house shall be taken by rent for the Lord King's service. And the whole weighing and marking of the second smelting shall be done there, and let none presume to make a second smelting, weighing, and marking elsewhere…' (Halsall 1998) (…in qualibet villa ubi fuerit secunda funtura extra muros civitatis Exoniae et extra villam de Bodmene constituatur una domus per conductionem domini Regis ubi fiat tota secunda funtura et ponderatio et signatio, et nullus praesumat alibi facere secundam funturam nec ponderationem nec signationem sicut...).

Smith's (1996 p96) suggestion that the two smeltings 'refer to smeltings of ore and slag' clearly makes no sense in this context.

The second smelting probably served to determine the quality of the tin metal prior to sale. In this respect, the coinage process as it was carried out 400 years later (see p144) was probably not very dissimilar to the weighing and stamping of the 13th Century. However, the use of a term denoting a high temperature process, albeit probably not smelting, implies that further refining of the metal may have occurred at the same time. Certainly the coinage process described by Kalmeter c.1725 involved the blocks of tin being re-melted and re-cast with some slag that had apparently been mixed with the metal being generated in the process (Brooke 1998 p81). That Mediaeval ingots had a lesser mass after the second smelting (…pro eo quod stagnum decidit in secunda funtura) is stated in De Wrotham's account of the weights.

The use of supposedly clean alluvial ores coupled with the relatively low temperatures and gentle reducing conditions generated in hand-blown furnaces would be expected to produce tin of very high purity. While it is possible that metallic elements more easily reducible than tin could be co-smelted with the tin, chemical analysis of prills trapped

in the Crift Farm slag showed such contaminants to be present only at trace levels, which would suggest that further refining was not necessary (although with no other slags from this period currently available for study, there is insufficient evidence to state whether this was the case for tin produced elsewhere, where ore quality may not have been so high). That Early Mediaeval tin ingots might have required refining is therefore interesting. The decline in tin quality observed when the smelters of Banca, Malaysia, switched from hand-powered to water-powered bellows has already been noted (p395), and this raises the question of whether water-powered bellows, which would provide a more vigorous draught and more strongly reducing conditions, were already in use in southwest England before AD 1200.

The date when blowing houses came into general use cannot be reliably established, as noted on p92. If, however, water-powered blowing houses were operating in De Wrotham's time, the fact that the weights of the second smelting are described as 'just and *ancient*' in 1198 (see p78) implies that refining had been necessary for some considerable period, and the introduction of the additional tax of 1 mark per thousandweight was not reflecting a change in technology. Its imposition was almost certainly political: at this time the level of taxation in England was very high generally and the exchequer would have been seeking additional sources of revenue to fund King Richard's military ventures.

Likewise the suggestion that the abolition of the payment on the tin of the second smelting in 1303 (see p78) 'may have resulted in part at least from the substitution of the single process in the blowing houses' (Worth 1953 p289), can probably be discounted on the grounds that the introduction of water-powered bellows would be more likely to reduce the quality of the tin and increase the need for a secondary

refining process. While the adoption of the blowing house may have occurred in the period around 1303, the change to a single tax is most likely to have been an attempt to streamline the collection of duty once the practice of farming the collection of the tax on the first smelting had ceased.

One final matter to be considered is the difference in the tax rates between Devon and Cornwall (see Table 1.1, p78), which were substantial, and persisted even up to the abolition of coinage in 1837 (Lewis 1908 p85). One possible explanation for why the Cornish were required to pay a far higher rate of tax is suggested by the slags from the blowing houses of the two counties. It is difficult to draw any firm conclusion when the number of Cornish samples is so limited, but analysis indicates that many of the slags from Devon are iron-rich, and so the possibility of iron being co-smelted into the tin produced at these sites is probably higher. If tin from Devon was recognized as being, in general, of slightly lower quality than Cornish tin, then the amount of tax charged on a Devon ingot may have been set lower to take into account the lower price that the ingot would fetch once sold.

Chapter 5

Conclusion

5.1: Conclusion

Of the four types of material found at smelting sites, slag is the most common and the most informative.

Two basic morphological types of slag occur: rod-like pieces of small size which may exhibit flow morphologies indicative of high viscosity, and slab-like pieces, which may be larger in size, with no flow structures suggesting greater fluidity when molten.

Four basic types of slag microstructure have been observed: glassy, feather/needle-phased, dendritic and fully crystalline. Glassy and feather-phased slags may additionally contain striations or 'flow banding' indicating incomplete mixing of ore and gangue minerals during slag formation.

High viscosity slags tend to be glassy or feather phased, and this is reflected in the glassy lustre of the samples; slab-like pieces that were more fluid tend to have dendritic or crystalline microstructures and thus appear duller.

The relationship between slag viscosity, microstructure and chemical composition is complex, but higher tin and/or tungsten content has been shown to promote the formation of a viscous glassy slag; iron and/or titanium content promotes the formation of dendritic phases and a more fluid slag, while iron ions promote fully crystalline microstructures.

Two main types of inclusion were observed in slags from all periods: fragments of gangue minerals and metallic prills. Relic gangue minerals that have not been

incorporated into the slag may derive from the ore or from recycled furnace linings. The observed size and numbers of mineral inclusions is generally consistent with the current understanding of ore processing methods, but insufficient variation exists to make this a useful characteristic for determining what level of technology was employed. Prills of metal were seen to be more common and of larger size in glassy slags, higher viscosity resulting in poor slag-metal separation. The majority of prills analysed were composed of tin metal with few impurities, but amounts and types of impurities varied where they did occur. Early slags contained only prills of pure (i.e. >99%) tin; prills in blowing house and later slags might be contaminated with iron, arsenic, tungsten or traces of other metals. Prill metal purity was seen to be loosely linked to slag composition with respect to iron but not to tungsten: prills of the tin-iron alloy hardhead were often present in slags with a higher iron oxide content (although owing to the increased fluidity of the slag, prills were rare in slags with the highest iron oxide content); tungsten could be detected in prills in only some of the slags with high tungsten oxide contents.

From a technological point of view, archaeological slags can be classified as early (i.e. produced in blast furnaces with a manually generated draught), blowing house (i.e. produced in blast furnaces equipped with water-powered bellows) or reverberatory. Industrially, reverberatory slags may be further sub-divided into top, middle and bottom pulled slags and glass slag.

Intuitively one would expect to see trends in slag characteristics as technologies changed, and some previous work on the subject (Tylecote et al 1989; Fielding 2001) has suggested that features such as residual tin content or microstructure can be used to identify slag of a particular historical period or produced using a particular technology.

However, these studies have been quite limited in extent, and a larger assemblage of material having been examined, it is apparent that the reality is somewhat more complex.

This is illustrated by the extent of the variation in composition and appearance of the blowing house slags that comprised the bulk of the samples analysed herein: blowing house slags could exhibit either of the two morphological types, any of the four microstructural types and had compositions that overlapped the ranges of both early and reverberatory slags for all the major elements present.

No single feature may therefore be taken as characteristic of the slags produced by a particular technology; morphology, microstructure, composition and types of inclusion must all be taken into account. At present the number of samples analysed is too small to allow meaningful multivariate statistical analysis.

The problem of identifying a slag of unknown provenance is further compounded by variations in slag composition resulting from chemical differences in the ore used in smelting. Geographical location and the characteristics of the local ore deposits must thus also be considered.

Major elements that have been shown to vary geographically are tin, iron, and tungsten. Moving from south-west Dartmoor to north-east Dartmoor a trend towards higher iron content and correspondingly lower tin content in early and blowing house slags was noted, which could be qualitatively related to mineral output from mines. High tungsten contents have been noted in slags from the western edge of Dartmoor. Slags from Cornwall may also evince strong geological signatures in their chemical compositions, but too few samples have, as yet, been located to identify trends. Geographical trends

are not apparent in the few reverberatory slags analysed; nor are they expected, as the ores smelted in this type of furnace derived from a very wide geographical area.

Of the several factors affect the composition of tin slags, the quality and composition of the ore used in smelting appears to have the most marked effect; this to a large extent masks features that arise as a result of the technology in use such as the type of fuel used, the construction of the furnace, the conditions under which the furnace was operated and the treatment of the slag subsequently.

Within the limits imposed by geological variation, however, certain features may be postulated as being characteristic of slags produced by the three different technological phases. Individual slag samples may exhibit some or all of these.

Characteristics of Early slags:

- Ropy or rod-like morphology
- Glassy lustre
- Possible weathering of exterior of sample to ochre silica glass
- Glassy microstructure
- Rare individual crystals of tin oxide or aluminium silicate within slag matrix
- Very high tin oxide content (15-60% SnO)
- Low iron oxide content (<10% FeO)
- Multiple large metallic prills trapped in slag matrix
- Prills of high purity (>99% Sn)

Characteristics of Blowing house slags

- Rod-like or slab-like morphology
- Any microstructure, determined by composition

- Variable tin oxide content (5-35% SnO)
- Variable iron oxide content (7-35% FeO)
- Variable numbers of metallic prills in slag matrix, depending on slag composition
- Prills of variable purity (many >99% Sn, but various contaminants (often Fe) can accompany tin.

Characteristics of Reverberatory slags:

- Slab-like morphology
- Very large fragments can occur (>10cm)
- Any microstructure, determined by composition and treatment during smelting, but many are crystalline
- Low tin oxide content (<20% SnO)
- Variable iron oxide content (5-30% FeO)
- High calcium oxide (lime) content possible
- Prills rare/absent and of small size
- Prills with various contaminants accompanying tin (mainly Fe, As, W).

Given that slag is rarely found in a dateable context, the ability to distinguish between slags produced by different technologies would be useful. Care must be taken to avoid getting into a circular argument: having classified a slag as early on the basis of its characteristics, conclusions should not be drawn about early smelting technique using samples from that site.

Several factors influence rate of reaction, metal quality and slag-metal separation. An optimum balance must be sought, taking into account the effect of ore quality, furnace type, smelting temperature, blast pressure and flux addition (if any). The complex, and

sometimes conflicting, interaction of these quantities means that is not possible to establish with any certainty what conditions prevailed during smelting, but trends may be suggested based on slag and prill compositions.

A furnace smelting ores with a high iron and/or titanium content probably operated at a higher working temperature; theoretical melting points are higher, and limited experimental work supports this. Since a higher temperature is achieved in a shaft furnace by increasing the draught strength, it follows that slag melting behaviour has an influence upon the extent to which co-reduction of iron oxides takes place with this technology. Analysis indicated reduced metal quality in some of the prills trapped in slag that had characteristics suggesting stronger reducing conditions. Sub-standard tin may also have been obtained as a result of slag recycling.

Using the observed compositional variation in slags from Dartmoor blowing houses as a proxy for metal quality, it may be suggested that the relatively iron-rich ores from north-eastern parts of the moor were less economical to smelt than the ores from elsewhere in Devon. Smelters producing contaminated metal would have found it necessary to carry out subsequent refining of their product, which is both time-consuming and adds to production costs, or sell it as a lower grade for a lower price.

Exploitation of these ores would thus be less likely in times when the demand for tin was low, or output dropped for social or political reasons (for example during the Civil War when what little production there was in Devon was concentrated around Tavistock and Ashburton Stannaries).

Tungsten is also problematical in smelting, and while tungsten minerals are not necessarily reduced to metal that would reduce the quality of the tin produced, their presence both raises the melting point of a slag in which they occur and increases the

viscosity of a slag at any given temperature. Avoidance of ores containing these minerals may in part explain the scarcity of blowing houses in the north-western quadrant of Dartmoor.

When considering periods prior to the introduction of the blowing houses, an understanding both of the smelting process and the mineralization of an area would assist in suggesting areas in which tin production is most likely to have occurred.

The calcium oxide content of all the slags examined is low compared to modern slags, indicating that lime was not added as a flux during smelting at any of the sites under consideration.

Waste metal, pieces of ore and fragments of furnace lining material are less well represented than slag in collections of material from tin smelting sites.

Ore samples deriving from prehistoric sites are characteristic of alluvial material or 'stream tin'. Analysis indicates that these pebbles are rich in tin, with cassiterite contents as high as 68%, but they are not devoid of gangue minerals. The lack of other smelting evidence at the find sites calls into question whether these pebbles were destined to be smelted for tin.

A piece of ore from the early Mediaeval Crift Farm site may have been eluvial cassiterite; it was very rich in tin, containing 75% SnO_2 overall. This ore could have been processed effectively using the basic stone hammers and crazing stone found at the site, and would have produced metal of the high purity suggested by the prills in the slag.

A piece of probable vein ore from Upper Merrivale, which had apparently been discarded on a waste dump, was shown to contain no more than 0.5% cassiterite.

In line with the evidence of standing remains on Dartmoor, examination of furnace lining samples indicates that the material of choice for the construction of the shafts of Devon blowing house furnaces was granite, although it appears that sandstone could also be used. Both types of rock are suitable for the purpose but granite is locally abundant. No samples from Cornish blowing houses have been located, but documentary evidence suggests the use of granite.

Firebrick and granite were recovered from 19th Century Eylesbarrow, which had both blast and reverberatory furnaces, though it was not possible to determine from which type of furnace these materials derived.

All the furnace material samples were vitrified beneath a very thin layer of slag.

Clay linings have been identified visually on a very small proportion of known samples, but no chemically distinguishable residual clay lining could be detected on the samples made available for analysis. This suggests that any clay lining originally present had a composition similar to that of the granite used to construct the shaft (which a locally sourced clay is likely to have had) and that the slag has reacted chemically with this clay layer, completely absorbing it. This is the most likely scenario based on documentary sources and evidence from in situ furnaces. Alternatively, clay may just have been used as a sealant around the edges of blocks, the low porosity of the vitrified granite making a full lining unnecessary.

Samples of what once had been metallic tin were obtained only from blowing house and earlier smelting sites; no material from reverberatory smelters was available. The majority of samples examined were oxidized throughout, either partially to SnO, or fully to SnO_2.

Compositional analysis of samples of metallic tin shows that tin produced in blowing houses and in earlier furnaces was of good quality. However, traces of other elements, including iron, copper, arsenic and lead have been detected. Metal from Trevellas Porth blowing house in Cornwall was shown to have a laminated structure, some phases containing traces of various metallic contaminants.

The difficulty in identifying the nature of pieces of metallic tin, whether as metal escaped through the furnace bottom or as refining waste, means that for samples not found in situ it is difficult to draw conclusions regarding the overall quality of metal produced at a site.

5.2: Further Work

While some understanding of the physical and chemical characteristics of slags produced by different technologies has been gained, it is not yet possible to identify a slag of unknown date with any certainty. In order to allow multi-variant statistical analysis, many more slag samples need to be obtained. Early and reverberatory slags are currently under-represented in the data, and while sites yielding the former are likely only to be discovered by chance, the locations of most reverberatory works are known and efforts should be made to recover material from these sites.

It is also necessary to obtain samples from blowing houses throughout Cornwall, as the effect of geological variation on the physical and chemical characteristics of Cornish blowing house slags has not yet been established owing to the dearth of this type of sample. The general location of many of the documented blowing houses is known, and it has been demonstrated on Dartmoor and Bodmin Moor that slag scatters occur in the vicinity of such sites.

Analysis of additional samples from those sites for which some compositional data has already been obtained will allow the range of variation for those sites to be established, improving the reliability of the model.

The difficulty of differentiating reverberatory slags from blast furnace slags is compounded by the fact that several chemically and morphologically distinct types of slag are generated in this process. Analysis of many more reverberatory slag samples would help to clarify the characteristics of each type. A study of modern reverberatory slags may be of use in this respect.

Slag recycling is another complicating factor in the interpretation of archaeological slags as it changes the character of the slag, but the extent to which this was carried out, particularly with regard to blowing house and earlier smelting, is unclear. As slag recycling produces tin contaminated with hardhead, additional analyses of entrained prills may serve to identify slags that were potentially produced as a result of this process. The question of whether a slag is a product of primary smelting or secondary slag recycling may then be addressed by considering the relative proportions of elements deriving from charcoal (calcium, potassium, magnesium and phosphorus, and to a lesser extent silicon, manganese and sodium), since having been through the furnace twice a recycled slag will have accumulated elements from double the amount of fuel ash.

In order to further elucidate the nature of blowing house furnace linings, chemical analysis using X-ray diffraction of pieces of clay from the in situ furnace linings at Upper Merrivale and Avon Dam may be carried out. Additionally, fragments of clay may be obtained from a small number of slagged granite samples, which appear to have a clay layer between the slag and the granite.

Documentary sources note the use of granite for the construction of Cornish blowing house furnaces, but also hint that other materials were used, possibly in areas where granite was not locally abundant. As archaeological evidence of Cornish furnaces is wholly lacking, further investigation of this issue would first require slagged and vitrified material to be located.

Appendix 1: Glossary of Terms

Adit	A horizontal tunnel running through a hillside to allow drainage of a mine, or removal of ore from it.
Alluvial (or detrital) tin	Tin ore that has been detached from a lode by weathering and has subsequently undergone erosion by the action of running water. Alluvial tin deposits may underlie an entire valley bottom and be buried under several metres of peat or gravel. Known colloquially as 'stream tin' as deposits often occur in the same vicinity as streams and rivers. (See also Streamwork). Alluvial tin can occur as pebbles or very fine sand. It is relatively free of gangue minerals.
Ashburton	A Stannary, or administrative district, of Devon (see Stannary); also a Stannary town (see Stannary Town).
Beam / Beamwork	Opencast pit for the extraction of cassiterite from lodes. The term was used only in Devon; in Cornwall openworks were known as 'goffens' or 'coffins'.
Blackmore	Stannary, or administrative district, of Cornwall covering the Hensbarrow granite upland north of St Austell (see Stannary).
Black tin	Colloquial term for a tin ore concentrate, usually containing c.63% tin and a small quantity of residual gangue minerals.
Blowing	In southwest England up until the 19th Century, smelting of cassiterite in a blast furnace to produce tin metal was referred to as

	‘blowing’ or ‘melting’ rather than smelting. (The term smelting was reserved for the process as it was carried out in reverberatory furnaces.) See also ‘Blowing House’ and ‘Tin Mill’.
Blowing House	A building in which the smelting of tin ore took place, containing a blast furnace and a bellows powered by a water wheel. Mechanical stamps for ore crushing may also have been housed within. Historically the term blowing house was used only in Cornwall. In Devon these buildings were referred to as tin mills.
Buddle	A rectangular or triangular pit in which cassiterite was washed after the ore had been crushed by the stamps. The lower density gangue minerals were washed away by a flow of water, while the dense cassiterite settled out and collected in the buddle. Later buddles were circular.
Burning House	A low-roofed building designed to allow the heat of a fire to be reflected down onto tin ore, which was spread thinly over a stone shelf, in order to roast it to remove impurities, particularly arsenic. Also known as ‘Tin Kilns’. In use from at least 1670. (See also Calcining).
Calcining	Roasting of ores on an open hearth in order to removed impurities such as arsenic and sulphides. This is carried out in a Tin Kiln in a Burning House.
Cassiterite	Tin oxide mineral (SnO_2): the main ore of tin.

Chagford	A Stannary, or administrative district, of Devon (see Stannary); also a Stannary town (see Stannary Town).
Coffin / Goffen	Opencast pit for the extraction of cassiterite from lodes. The term, used in mine names from at least 1503, was used only in Cornwall; in Devon openworks were known as 'beams'.
Coinage	The process of weighing, quality testing and paying duty upon newly smelted tin ingots. This was carried out twice yearly, at Midsummer and Michaelmas (29th September) at a Stannary town in the presence of officials appointed by the Crown.
Crazing	To use of a pair of circular granite millstones to crush tin ore; mills dedicated to this purpose are Crazing Mills.
Eluvial tin	Tin ore that has been detached from a lode by weathering but which has not been subjected to erosion by the action of running water. Commonly found in dry shallow valleys above larger rivers. This type of ore is known colloquially as shode or shoad. May also have been referred to as moor-tin.
Farm (of tax)	Lump sum (based on an estimation of the value of the tax revenue) paid to the Crown by a private individual for the right to collect the tax and claim the proceeds.
Float / Floatstone	A shallow trough cut into a stone (usually granite) slab into which the molten tin and slag from a blowing house furnace flowed during smelting.

Foot	A measure of volume of tin ore concentrate, equating to 2 gallons. The mass of tin ore in a foot varied according to the quality of the ore it contained, but was probably in the range of 24-36 kg; these values for vein ores and alluvial/eluvial ores respectively.
Foweymore	Stannary, or administrative district, of Cornwall covering Bodmin Moor (see Stannary).
Gangue	Minerals other than cassiterite that are present in tin ore.
Goffen	See Coffin.
Gossan	An iron-rich rock found on the top of exposed mineral lodes, which also contains tin minerals in locations where these occur. Gossans are formed by the migration of soluble minerals through the rock into the lower zones of the lode; insoluble minerals such as tin and iron remain in the upper parts.
Hardhead	An alloy of iron and tin. It is magnetic and has a higher density than pure tin, so sinks to the bottom of a refining basin. Also known as Mount-Egge in 17th Century.
Hundredweight or Hundred (cwt)	1. A unit of mass equating to 112 lb avoirdupois (Imperial measure). The avoirdupois measure of 112 lbs was used in reverberatory smelting houses for the sale of tin ore and for the sale of tin ingots after coinage (Kalmeter (trans Brooke 1998 p351)). 2. The Stannary or long hundredweight is variable depending upon the circumstances of use, and the issue of its value is confused.

	Examples of the Cornish Stannary hundredweight are: Kalmeter (1724 translated Brooke 1998 p350) = 120 lbs (for coinage of tin ingots from Cornish blowing houses); Hatcher (1970 p24, 1973 p21) = 100 lbs. Examples of the Devon Stannary hundredweight are: Dr Cotton (1664) = 120 lbs; Kalmeter (1724 translated Brooke 1998 p350) = 100 lbs (for coined tin ingots from Devon blowing houses); Hatcher (1970 p24, 1973 p21) = 120 lbs. Lewis (1908) = 120 lbs (no distinction between Devon and Cornwall).
Jew's House	Whimsical term, used from the Elizabethan period through to the 19th Century, to denote an old smelting site. Traditionally it was believed that, until their expulsion from England in 1290, the Jews were involved with smelting. It became the fashion to explain smelting-related finds in terms of a semi-mythical past, so old smelting places, including some that are now known to date to the 17th Century, were referred to as Jew's Houses.
Leat	Artificial channel carrying water.
Lode back mining	A method of ore extraction using a series of small pits, which follow the course of a shallow tin-bearing mineral vein.
Mark (money)	1 mark = 13s 4d (shillings and pence) = 160d (pence). The mark did not exist as a coin.

Melting	In southwest England up until the 19th Century, smelting of cassiterite in a blast furnace to produce tin metal was referred to as 'blowing' or 'melting' rather than smelting. (The term smelting was reserved for the process as it was carried out in reverberatory furnaces.) See also 'Blowing House'.
Mine tin	Term used in 16th and 17th Centuries for vein ore.
Mispickel	The mineral arsenopyrite (FeAsS), known by the tinners as silver mundick or mispickel. The term mispickel is also used for other arsenical minerals such as löllengite ($FeAs_2$).
Moor tin	Term used in 16th and 17th Centuries for tin ore from streamworks. Appears to have been used occasionally to distinguish eluvial cassiterite from alluvial cassiterite (stream tin).
Mortar stones	Flat stones that were placed beneath the heads of stamping machinery, upon which ore was crushed. Discarded mortar stones found at tin mills appear as blocks of granite with two or three bowl shaped depressions worn into the surface, which has been caused by the pounding of the stamp heads.
Mundick	The minerals iron pyrite (FeS), called mundick (or mundic) by the tinners, and arsenopyrite (FeAsS), known as silver mundick or mispickel.
Openwork	Opencast pit for the extraction of cassiterite from lodes, consisting of a relatively deep (up to 60m), elongated gully or quarry. See also

	‘goffen’, ‘coffin’ and ‘beam’.
Penwith and Kerrier	Stannary, or administrative district, of Cornwall covering Land's End and the Lizard peninsulas (see Stannary).
Pillion Tin	Metallic tin (usually in the form of prills) trapped in slag after smelting, which is recovered by mechanical separation and subsequently re-melted.
Pipe Roll	A series of financial records used by the Exchequer to record Crown incomes (including revenues from the taxation of tin) and expenses.
Plympton	A Stannary, or administrative district, of Devon (see Stannary); also a Stannary town (see Stannary Town).
Prill	A small spherical inclusion of metal trapped within solidified slag.
Reverberatory	A method of smelting that employs a furnace with a low arched roof to reflect heat from a fossil fuel onto a bed of ore.
Romarchite	Tin mineral (SnO), occurs as a re-oxidation product on tin metal.
Shilling (money)	1s (shilling) = 12d (pence) 20s (shillings) = £1 (pound)
Shoad / Shode	See Eluvial tin.
Smelting	The reduction of metal from its ore. As it was applied to tin, the term only came into common use in the 18th Century, when it was

	used to describe the process of obtaining tin metal from cassiterite using a reverberatory furnace. Tin smelting in a blast furnace was referred to as blowing or melting rather than smelting.
Stamps / Stamping	A device used to pulverize ore/Using Stamps to crush ore. Stamps consist of a row of heavy vertically mounted beams, often iron-shod, that are lifted by means of waterpower, then allowed to fall onto granite blocks or 'mortars', thus crushing the ore between. Dry ore stamping was replaced by wet stamping.
Stannary	From at least the early Mediaeval period, the tin industry was under the legal and administrative control of a body known as the Stannary Court, which gave those connected with tinworking their own laws and privileges, and ultimately their own parliament. The Stannaries were the administrative districts under this system, and were based around the tin-bearing areas of Devon and Cornwall (see Blackmore, Foweymore, Penwith, Tywarhaile, Ashburton, Chagford, Plympton and Tavistiock). Each Stannary had designated Stannary towns where tin was taken for coinage (see Coinage and Stannary Town).
Stannary Town	The administrative centre of a tin-bearing area or Stannary, where coinage was carried out. For Devon: Ashburton, Chagford, Tavistock and (later) Plympton. For Cornwall: Truro, Helston, Lostwithiel, Bodmin (supplanted later by Liskeard) and (later) Penzance.

Stannite	Tin mineral (Cu_2FeSnS_4), much less common than cassiterite.
Stream tin	See Alluvial tin.
Streamwork	An excavation for the extraction of alluvial or eluvial tin ore, within which a flow of water was used to wash away lighter particles of clay, sand or gravel, leaving behind the higher density tin ore.
Tavistock	A Stannary, or administrative district, of Devon (see Stannary); also a Stannary town (see Stannary Town).
Thousandweight or Thousand (Mwt)	A unit of mass equating to 10 hundredweights (see Hundredweight).
Tide	Term used in blowing houses – a smelting period of 12 hours.
Tin Kiln	See Burning house.
Tin Mill	Term used in Devon to denote a building in which stamping, blowing or both took place. See also ‘Stamping’ and ‘Blowing House’.
Turbary	An area from which peat turfs are extracted.
Tywarnhaile	Stannary, or administrative district, of Cornwall covering the St Agnes and Carn Brea areas (see Stannary).
White tin	Colloquial term for tin metal.

Appendix 2: Reported Slag Finds not included in this Work

A single piece of slag is reported to have been found during the construction of a conservatory at Blowing House Cottage, Godolphin (SW60333205), which stands on the site of a definite stamping mill (Lawson-Jones 2000). The material, which was excavated by Cornwall Archaeology Unit, was not available for analysis (Lawson-Jones pers comm. Aug 2003). Confirmation of the identity of this sample would support the case that Godolphin Blowing House really did stand on the site. A search of the area by the author in 2004 yielded no physical evidence for smelting having taken place in the vicinity of the cottage, nor was any slag found by Greeves (pers comm. 2004) who has also examined the site.

Slag has been located in the stream bank beside the blowing house at Coombe, Millpool (SX12297070), and is reported by Sharpe (Herring 2005) of the Cornwall Archaeological Unit. No samples have yet been collected.

A single piece of slag was discovered at the Middle Merrivale blowing house (SX55277624) during a guided tour given by Dr Greeves. This was taken by its finder, whose identity is not recorded (Greeves pers comm. 2004). Visits to this site by several researchers including Worth, Greeves, and the present author have failed to detect any other trace of slag.

Possible tin slag from Elfordleigh mill (SX545586), which was lodged in Plymouth City Museum by Dr Greeves, could not be located by the curator. Material from the same collection from Widecombe and Outcombe mills was shown by XRF analysis to be iron slag.

The single bead of slag from Dean Moor (SX678653), which was lodged in Exeter City Museum following excavations of the Bronze Age settlement site (Fox 1957), could not be located. It is currently believed to be at Exeter University.

Slags from a Romano-British settlement site at Killigrew Round (SW84685133), excavated by Cornwall Archaeology Unit in 1996 (Anon 1996-7), were believed to contain tin (Richard Cole pers comm.2002), however analysis of several pieces of this material by the author using a range of means failed to detect any traces of tin.

A single fragment of possible tin slag and a slag-coated pebble from a potentially early smelting site at Botallack Bunny (SW3643433458) were found during excavations by Cornwall Archaeological Unit (Adam Sharpe pers comm. 2005). Analysis by the author showed it to be copper slag containing prills of copper metal.

Although tin slags have been identified previously, samples from Impham Quay Smelter (SX43987055), sent to the author by Mr Brooke, proved to be lead slags.

A fragment of black glassy-appearing material that resembled slag collected at Black Tor Falls mills (SX57497161) by Mr Owen Baker proved to be a geological specimen.

Appendix 3a: Descriptions of Selected Slag Samples

Site (with sample number if applicable)	**Mass /g**	**Description**
Avon Dam	1.1	The slag changes colour from black to dark grey from the edge of the sample towards the centre. Matt appearance. Surface stained with iron oxide. Some inclusions and relatively large vesicles, up to c.2mm. No prills visible.
Avon Dam	2.5	The slag changes colour from black to dark grey from the edge of the sample towards the centre. Matt appearance. Surface stained with iron oxide. Some inclusions and relatively large vesicles, up to c.2mm. No prills visible.
Avon Dam	1.6	The slag changes colour from black to dark grey from the edge of the sample towards the centre. Matt appearance. Surface stained with iron oxide. Some inclusions and relatively large vesicles, up to c.2mm. No prills visible.
Avon Dam 2/20	0.5	Sample had suffered recent breakage. Freshly exposed slag glassy black; elsewhere surface was weathered. One vesicle c.1mm. One small sub-mm inclusion. No prills visible.
Blackaller 4/22	18.8	Black glassy slag with iron staining on surface. A few small vesicles. No inclusions or prills visible.
Butterbrook 2/33	2.0	Black glassy slag with rust brown weathered surface. A few small vesicles, the majority <1mm. Inclusions c.2-3mm. No tin prills visible.
Butterbrook 2/34	3.7	Black glassy slag with rust brown weathered surface. A few small vesicles, the majority <1mm. Inclusions c.2-3mm. No tin prills visible.
Butterbrook	2.9	Black glassy slag with rust brown weathered surface. A few small vesicles, the majority <1mm. Inclusions c.2-3mm. No tin prills visible.
Caerloggas 3/44 and 3/45	9.2	Sub-rectangular fragment 20 x 30 x 5mm. Smooth weathered surface with occasional c.1mm indentations on one flat face. Surface black, streaked golden brown, with a silky lustre. The interior is glassy black. Conchoidal fracture. A small number of sub-mm crystalline inclusions. Non-magnetic.
Carvedras 3/30	1.8	Irregular shape: 20 x 10 x 5 mm. Black slag with silky lustre. Two vesicles c.4mm visible. One inclusion c.2mm. Non-magnetic.
Charlestown 4/20	21.5	Black slag with silky lustre. No vesicles or prills visible. Some large inclusions, up to 2mm.

Crift Farm 4/15	12.5	Black to dark brown glassy slag with a few vesicles and inclusions up to 1mm. No prills visible. Flow morphology.
Crift Farm 4/16	8.3	Black to dark brown glassy slag with a few vesicles and inclusions up to 1mm. No prills visible. Rod-like morphology.
Crift Farm 4/17	15.0	Black to dark brown glassy slag with a few vesicles and inclusions up to 1mm. No prills visible. Flow morphology.
Crift Farm 4/27	17.9	Black to dark brown glassy slag with a few vesicles and inclusions up to 1mm. No prills visible. Flow morphology.
Ditsworthy 3/01	2.4	Rod-like morphology. 10 x 20 x 5mm. Dull weathered black surface. Conchoidal fracture. Narrow light brown bands visible within the glassy black slag on freshly exposed surface. Several <1mm inclusions. No vesicles or tin prills.
Doe Tor Green 2/12	0.1	Weathered surface is iron stained. Freshly exposed surface shows black and brown bands. Silky lustre. No tin prills.
Drakeford Bridge	0.2	Black slag with silky lustre. Weathered surface. No vesicles or inclusions. No prills visible.
Drakeford Bridge	0.5	Black slag with silky lustre. Weathered surface. No vesicles or inclusions. No prills visible.
Drakeford Bridge 2/19	0.6	Black slag with silky lustre. Weathered surface. No vesicles or inclusions. One very tiny possible tin prill.
Eylesbarrow 2/35	34.1	Matt black slag, weathered on surface to a purplish-grey colour. Several small vesicles, majority <1mm, some up to 3mm. No inclusions or tin prills visible. A section of the surface has the ropy appearance of a viscous material that has flowed, and three nodules on other surfaces may be solidified drips of slag.
Eylesbarrow 4/05 & 4/06	193	A block of slag measuring 60 x 35 x 55mm. Appears to have been broken off a still larger piece. Smooth glassy black slag on upper surface, grading through to reddish-maroon on the bottom. Many inclusions of quartz measuring up to 5mm across are embedded in the bottom of the block. Upper part analysed as 4/05 and lower part as 4/06. Non-magnetic.
Glazebrook	0.3	Black glassy slag with weathered surface. Some very small, <1mm, vesicles. No inclusions or prills visible.
Glazebrook 2/58	0.4	Glassy black slag with weathered surface. A few vesicles of c.1mm. No prills or inclusions observed.
Gobbett 2/28	2.2	Glassy black slag with weathered surface. Some inclusions, but no vesicles or prills visible.
Hurdon 2/01	0.2	Small fragment of glassy black slag. Some very small vesicles. No prills or inclusions visible.
Hurdon 4/26	0.1	Small fragment of glassy black slag. No vesicles, prills or inclusions visible.

Lether Tor Farm 2/11	1.5	Glassy black slag with weathered surface. Rod-like morphology. Occasional small vesicles up to 2mm. No inclusions or prills visible.
Lingcombe 3/19	0.7	Glassy black slag. No inclusions, vesicles or prills visible.
Lingcombe 3/20	2.4	Black slag with silky lustre. Rod-like morphology, with possible drips. No inclusions, vesicles or prills visible.
Lingcombe	38.8	Black slag with silky lustre. No inclusions, vesicles or prills visible.
Longstone 2/06	2.3	Black glassy slag with several elongated vesicles and possible prills. Occasional small <1mm inclusions.
Longstone 2/07	3.7	Black glassy slag with a few vesicles and possible prills. No inclusions visible.
Longstone 2/47	3.2	Black glassy slag. A few large vesicles up to 2mm. Inclusions up to 2mm. No prills visible.
Longstone 4/24	4.1	Black glassy slag. Some vesicles up to 1mm. No prills or inclusions visible.
Lustleigh	47.4	Black slag with silky lustre, clearly broken off a larger piece. The upper and lower faces of the sample are flat, with a wrinkly appearance, suggesting a 2cm thick layer of slag solidified whilst overlying a level surface. Many vesicles, up to 4mm, concentrated on one face of the sample, possibly the upper surface. No inclusions or prills visible.
Lustleigh 2/50	13.9	Black slag with silky lustre, clearly broken off a larger piece. A few vesicles, up to 4mm, concentrated on one face of the sample, possibly the upper surface. No inclusions or prills visible.
Lustleigh 2/51	37.4	Black slag with silky lustre, clearly broken off a larger piece. A few vesicles, up to 4mm, concentrated on one face of the sample, possibly the upper surface. No inclusions or prills visible.
Lower Merrivale	0.3	Irregular fragment 7 x 11 x 3mm. Glassy black slag showing conchoidal fracture.
Lower Merrivale 4/04	4.0	Irregular fragment 15 x 8 x 15mm. Glassy black slag showing conchoidal fracture.
Lower Merrivale 4/28	1.5	Glassy black slag showing conchoidal fracture. A few very small vesicles.
Upper Merrivale		Results given in separate table -see Appendix 3b
Metherel 2/48	6.7	25 x 15 x 10mm. Black glassy slag with some weathering of surface. Surface exhibits flow morphology. Several inclusions measuring up to 2mm. A few small <1mm vesicles. No tin prills observed.
Metherel 2/49	8.1	20 x 15 x 15mm. Black glassy slag with some weathering of surface. Surface exhibits flow morphology. A few small <1mm vesicles. No inclusions or tin prills observed.
Nosworthy 3/16	0.2	Glassy black slag. No visible prills. Extremely vesicular with vesicles up to 5mm. A few rare inclusions of sub-mm size.
Nosworthy 3/17	0.4	Glassy black slag. No visible prills. Extremely vesicular with vesicles up to 5mm. Large inclusion, 3mm across.

Outer Down 4/18	4.7	Black slag, with many large vesicles up to 2mm. Several inclusions up to 2mm. No prills visible.
Retallack 4/01	0.4	Irregular shape: 6 x 5 x 9mm. Glassy black slag. Conchoidal fracture. A few vesicles measuring up to 1mm.
Retallack 4/02	0.4	Irregular shape: 8 x 7 x 5mm. Glassy black slag. Conchoidal fracture. One inclusion c.1 x 2mm.
Retallack 4/03	0.5	Irregular shape: 9 x 9 x 2 mm. Glassy black slag. Conchoidal fracture. Several inclusions <1mm.
Retallack	1.3	Irregular shape: 14 x 8 x 8mm. Glassy black slag. Conchoidal fracture. Several inclusions up to 1mm.
Retallack	0.5	Irregular shape: 9 x 6 x 5mm. Glassy black slag. Conchoidal fracture. One large vesicle c.2mm.
Retallack	0.3	Irregular shape: 9 x 6 x 3mm. Glassy black slag. Conchoidal fracture. Several inclusions <1mm.
Riddon	3.3	Black glassy slag with heavily weathered surface. Inclusions up to 2mm. A small number of <1mm vesicles. No tin prills visible.
Riddon 2/38	4.2	Black glassy slag with heavily weathered surface. Very small inclusions visible. No tin prills visible.
Riddon 2/39	1.3	Black glassy slag with heavily weathered surface. No vesicles, inclusions or prills visible.
South Hill I 2/42	5.0	Black glassy slag. No vesicles, prills or inclusions. None of the surfaces are worn or corroded.
South Hill I 2/43	14.5	Black glassy slag. Contains a large proportion of granitic material, which may be furnace lining, that appears as an area of densely packed white speckles <1mm in diameter surrounded by black glassy slag, confined to one half of the sample. Several vesicles up to 3mm. No prills visible.
South Hill II 2/17	0.8	Glassy slag, weathered on outer surface. No inclusions, prills or vesicles visible.
Stannon Brook 2/02	4.1	Glassy black slag. A few small vesicles. No inclusions visible. Possible prills visible.
Stannon Brook 2/03	6.4	Glassy black slag. A few small vesicles and inclusions <1mm. Possible prills visible.
Stannon Brook 2/04	7.2	Glassy black slag. Several vesicles up to 1mm. Inclusions up to 1mm. No prills visible.
Stannon Brook 4/25	2.4	Glassy black slag. No inclusions, vesicles or prills visible.
Taw River	14.5	Black glassy slag with narrow bands of light brown. Surface weathered to a dull purplish-grey. Ropy morphology. Several large vesicles up to 8mm. Occasional <1mm inclusions. No tin prills visible.
Taw River 2/15	1.7	Silky slag with weathered surface. No vesicles or inclusions. One very small possible tin prill noted.
Taw River 2/40	8.8	Black glassy slag with narrow bands of light brown. Surface weathered to a dull purplish-grey. Several vesicles. Occasional <1mm inclusions. No tin prills visible.
Taw River 2/41	4.3	Black glassy slag with narrow bands of light brown. Surface weathered to a dull purplish-grey. Several vesicles <1mm. Occasional <1mm inclusions. No tin prills visible.
Teignhead Farm 2/14	0.4	Glassy slag with weathered surface. Vesicles and possible tin prills present. No inclusions.

Thornworthy	36.5	Black slag with silky lustre. Weathered surface iron stained. One surface has a slightly ropy texture, and there is a hint of another face on the opposing side of the sample, suggesting the slag solidified in a layer 2.5 – 3cm thick. Several very large vesicles with an elongated shape. No inclusions or tin prills visible.
Thornworthy 2/45	13.2	Black slag with silky lustre. Weathered surface iron stained. A small number of vesicles 1-2mm. A fragment of charcoal or some other woody material is enclosed within a cavity. No inclusions or tin prills visible.
Thornworthy 2/46	7.6	Black slag with silky lustre. Weathered surface stained with iron oxide. No vesicles, prills or inclusions visible.
Trereife/ Stable Hobba	>100	Several sub-rectangular blocks examined. Some pieces quite massive, up to 20cm long and clearly broken off larger blocks. Dark grey slag with some iron staining on outer surface. Silky lustre. Clear differences between upper and lower surfaces: one highly vesicular, the other smoother.
Trereife/ Stable Hobba 3/35 and 3/36	170	Sub-rectangular block: 45 x 45 x 40mm. Dark grey with a slightly silky lustre. Very slight iron staining. Three faces have a coating of a powdery white material. One of these faces is vesicular with vesicles c.2mm. Other faces contain a few elongated channels. Non-magnetic.
Trereife / Stable Hobba 4/21	25.4	Large irregular shaped lump of black slag with silky lustre. No inclusions, vesicles or prills visible.
Trevellas Porth 4/19	11.8	Black glassy slag with occasional very small sub-mm inclusions. No vesicles or prills visible.
Wallabrook 3/18	2.7	Black slag with silky lustre. No visible inclusions, vesicles or prills.
Wapsworthy 2/29	14.1	15 x 35 x 10 mm. Matt black slag with slight weathering of surface. Flow morphology. A small number of vesicles up to c.5mm. Some small inclusions. No prills visible.
Wapsworthy	0.4	Relatively flat fragment 5 x 20 x 2mm. Black glassy slag with slight weathering of surface. No vesicles, prills or inclusions visible.
Week Ford 4/23	1.1	Small highly abraded fragment of black glassy slag. No inclusions, vesicles or prills visible.
Weir Quay 2/18	9.0	Black slag with silky lustre. A few vesicles c.1mm. No inclusions. Possible prills visible.
Whitten Knowles	4.2	Black glassy slag. Ridged surface: flow morphology. One large 6mm inclusion, one 1mm inclusion. Vesicles up to 5mm, some elongated.
Whitten Knowles 2/36	17.1	Black glassy slag, with streaks of brown. Outer surface weathered to a dark gold. Flattened shape. No vesicles, tin prills or inclusions visible.
Whitten Knowles	8.0	Black glassy slag, weathered to a dull grey-green over most of its outer surface, with some iron staining. The surface is wrinkled.

Lower Yealm Steps 2/13	1.1	Dark grey slag with a silky lustre. Weathered outer surface of sample is iron stained. No inclusions, prills or vesicles.
Lower Yealm Steps 3/31	5.2	Glassy black slag with dull weathered surface. Occasional small inclusions. No vesicles. Conchoidal fracture.
Lower Yealm Steps 3/32	5.7	Glassy black slag, heavily iron stained on surface. The slag appears laminated.
Upper Yealm Steps 2/10	0.4	Black slag with silky lustre. Rod-like morphology. Possible prills visible.
Yellowmead	<0.1	Black glassy slag. A slightly curved, narrow rod in shape. No prills, vesicles or inclusions visible.
Yellowmead	<0.1	Black glassy slag. A few vesicles, 1mm or less. Inclusions (visible as white flecks) c.1mm.
Yellowmead 2/44	1.3	Black glassy slag. A few vesicles, 1mm or less. Inclusions (visible as white flecks) c.1mm.
Yes Tor Bottom 2/60	10.3	Black glassy slag. Parts of surface weathered to a dull grey. Weathered area is iron-stained. Vesicles up to 2mm. Inclusions up to 5mm. No prills visible.
Yes Tor Bottom	14.4	Black glassy slag. Parts of surface weathered to a dull grey. Vesicles up to 2mm. Inclusions up to 5mm. No prills visible.
Yes Tor Bottom	12.1	Black glassy slag. Parts of surface weathered to a dull grey. Vesicles up to 2mm. Inclusions up to 5mm. No prills visible.

Appendix 3b: Descriptions of Selected Slag Samples from Upper Merrivale

Note: Context numbers given in column 1 refer to the contexts from which slag was recovered in the original excavation (Gerrard and Greeves 1991, 1992a; Greeves 1993b, Greeves and Newman 1994). A description of these contexts is appended below. Samples that have been analysed in this work are shaded and the sample numbers are entered beneath the context numbers.

Context No	Texture	Colour	Condition	Inclusions	Vesicles /mm	Prills	Mass /g	Comments
364 *2/52*	Glassy	Black + Brown streaks	Worn / Broken	Present	3	None	7.1	Very dissimilar slag from same context.
364	Matt	Black	Worn / Broken	Present	5	Prills	36.6	Very dissimilar slag from same context.
503 *2/22*	Glassy	Black	Worn / Broken	Present	5	None	3.5	
142 *2/53*	Glassy	Black	Worn / Broken	Present	<1	None	8.5	Flow morphology.
446	Glassy	Black	Worn / Broken	Present	1	None	5.0	
446 *2/21*	Glassy	Black	Worn / Broken	Present	1	None	1.2	
756 *2/23*	Glassy	Black	Worn / Broken	Present	5	None	1.5	
756	Glassy	Black	Worn / Broken	None	1	None	0.5	
798 *3/24*	Glassy	Black	Worn / Broken	Present	3	None	30.1	

798	Silky	Grey (prismed)	Broken	None	3	None	10.7	Discolouration of outer worn layer.
210	Glassy	Black	Worn / Broken	Present	0	Possibly	11.5	Flow morphology.
210	Glassy	Black	Worn	None	0	None	4.8	
210 *2/25*	Glassy	Black	Worn	Present	0	None	3.5	
368	Glassy	Black	Worn / Broken	None	0	None	2.4	
368	Glassy	Black	Worn / Broken	Present	2	None	6.4	Quite large inclusions (~4mm).
368	Matt	Iron stained	Worn	Present	5	None	30.3	Lumpy upper surface, smooth lower. Iron staining.
368	Silky	Iron stained	Worn / Broken	None	1	None	57.8	Lumpy and bubbled upper surface, smooth lower surface. Iron stained.
495 *2/54*	Matt	Iron stained	Worn / Broken	Present	4	None	22.6	Lumpy and bubbled upper surface, smooth lower surface. Iron stained.
495	Glassy	Black + Brown Streaks	Broken	Present	2	None	3.4	
528	Glassy	Black	Broken	Present	0	None	0.6	
528	Glassy	Black	Broken	Present	0	None	3.6	
528	Glassy	Black	Broken	Present	0	None	1.5	
528	Glassy	Black	Broken	Present	0	None	0.5	
528	Glassy	Black	Broken	Present	0	None	1.4	
528	Glassy	Black	Broken	Present	0	None	0.7	
528	Glassy	Black	Broken	Present	0	None	1.0	
528	Glassy	Black	Broken	Present	0	None	0.5	
528	Glassy	Black	Broken	Present	0	None	0.4	

528	Glassy	Black with gold stain	Worn	None	0	None	6.4	Flow morphology.
528	Glassy	Black with gold stain	Worn	None	0	None	1.2	
528	Matt	Black	Worn	Present	0	None	2.4	Suspected stone containing quartz and black mineral.
528	Glassy	Black	Broken	Present	2	None	4.6	Large number of inclusions.
558	Glassy	Black	Worn / Broken	Present	0	None	9.9	
558	Glassy	Black with gold stain	Worn / Broken	Present	0	None	6.7	
558	Glassy	Black	Worn / Broken	Present	0	None	2.4	Flow morphology.
969	Glassy	Black	Worn / Broken	Present	0	None	0.4	
969	Glassy	Black	Worn / Broken	Present	0	None	0.6	
969	Glassy	Black with gold stain	Worn / Broken	Present	2	None	1.2	
969	Glassy	Black	Worn / Broken	Present	5	None	3.1	
969	Glassy	Black	Worn / Broken	Present	10	None	4.1	
969	Glassy	Black	Worn / Broken	Present	5	None	6.0	
993	Glassy	Black	Broken	Present	1	None	1.5	Possibly has cooled resting on flat surface.
993	Glassy	Black	Broken	Present	5	None	1.9	
993	Glassy	Black	Broken	Present	1	None	0.5	

58	Glassy	Black with gold stain	Broken	None	0	None	0.6	
774	Glassy	Black	Broken	Present	1	None	1.0	
1509	Glassy	Black	Broken	Present	0	None	3.8	
1509 *2/31*	Glassy	Black with gold stain	Worn	None	5	None	1.4	
565	Glassy	Black	Worn / Broken	Present	0	None	7.9	Flow morphology.
565	Glassy	Black	Worn / Broken	Present	0	None	0.6	Flow morphology.
565	Glassy	Black	Worn / Broken	Present	0	None	0.5	Flow morphology.
565	Glassy	Black	Worn / Broken	Present	1	None	0.4	Flow morphology.
978	Glassy	Black + Brown Streaks	Broken	Present	2	None	14.9	
978	Glassy	Black	Worn	None	0	None	0.4	Flow morphology.
978	Glassy	Black	Worn	Present	1	None	0.8	
773 *3/27*	Matt	Iron stained	Worn	Present	10	None	46.5	Flat bottom and sides, lumpy upper. Most bubbles at top.
773	Glassy	Black	Worn	Present	0	None	4.9	
1527	Glassy	Black	Worn	Present	0	Prills	1.1	
970	Glassy	Black	Worn / Broken	Present	0	None	4.0	Flow morphology.
970	Glassy	Black	Broken	Present	0	None	2.6	
970 *2/26*	Glassy	Black	Broken	Present	1	None	1.0	
970	Glassy	Black	Broken	Present	0	None	0.5	

979	Glassy	Black	Worn / Broken	Present	0	None	16.5	
979	Glassy	Black	Worn / Broken	Present	0	None	2.7	
979	Glassy	Black	Broken	Present	2	None	1.1	
979	Matt	Black	Worn / Broken	None	0	None	4.5	
979	Glassy	Black	Worn	None	0	None	0.4	Flow morphology.
482	Glassy	Black	Broken	Present	0	None	0.5	
482	Glassy	Black	Broken	Present	0	None	1.8	
482	Glassy	Black	Broken	Present	0	None	1.4	
482	Glassy	Black	Broken	Present	0	None	1.1	
482	Glassy	Black	Broken	Present	0	None	0.4	
482	Glassy	Black	Broken	Present	0	None	0.4	
482	Glassy	Black	Broken	Present	2	None	0.3	
482	Glassy	Black	Broken	None	0	None	0.1	
482	Glassy	Black	Broken	Present	1	None	1.5	
482	Glassy	Black	Broken	Present	0	None	0.5	
482	Glassy	Black	Worn	Present	0	None	0.4	Flow morphology.
482	Glassy	Black	Worn / Broken	Present	2	None	2.7	
482	Matt	Black	Worn	None	0	None	2.0	Flow morphology?
482	Glassy	Black	Worn / Broken	None	0	None	0.8	Flow morphology.
482	Glassy	Black	Worn	None	0	None	0.2	Flow morphology.
124	Glassy	Black	Worn / Broken	Present	1	None	3.0	

124 *2/56*	Glassy	Black	Worn	None	0	None	1.7	
718	Glassy	Black and blue	Worn / Broken	Present	0	None	3.2	Blue colouring on part of surface.
121 *2/32*	Matt	Brown	Worn / Broken	None	1	None	27.0	Smooth sides, slightly rough upper surface. Base has rock impression.
901 *2/24*	Glassy	Black	Broken	Present	2	None	8	
164 *2/57*	Glassy	Black	Worn / Broken	Present	0	None	2.6	
164	Glassy	Black + brown streaks	Worn / Broken	Present	0	None	31.5	Smooth base and sides, rough upper surface.
433 *2/27*	Stony	Iron stained	Worn / Broken	Present	5	None	280.4	Smooth base and sides. Bubbles in rough upper part.
395 *2/55*	Glassy	Iron stained	Worn	None	0	Prills	3.1	Possible prills.
395	Glassy	Black	Broken	Present	3	None	1.6	
448	Glassy	Black	Worn	None	1	None	2.0	Piece of charcoal embedded.
1512	Glassy	Black with gold stain	Broken	Present	5	None	2.2	Gold stain on surface.

Context No	Description of Context
58	Bellows platform Mill A.
121	Possibly late. Marks end of or post-dates last stamping phase but predates last furnace phase. Outside Mill B in ore dump.
124	Mill A below wall, i.e. pre-dates rebuild of Mill A.
142	Mill B, base of east wall, i.e. pre-dates Mill B.
164	Mill B, possible fill of stamping pit.
210	Possibly old? Associated with Romano-British or later Prehistoric pot sherd. North end of upper trench.
364	Mill B outside. Mediaeval 14^{th} – 15^{th} C jug in same context. Under wall tumble.
368	Outside Mill B, south of possible entrance.
395	Mill B, against north side of in-situ mortar stone. Relates to later stamping phase?
433	Leat embankment. Upper fill of leat. Leat is relatively early so must relate to early stamping phase, thus must have been abandoned by time leat embankment built.
446	Leat embankment, under south side of revetment. Pre-dates leat embankment which is the last phase of stamping.
448	Leat embankment.
482	Fill of stamps pit? (possibly earlier) Mill B.
495	Mill B outside, wall built on it.
503	Contemporary or earlier than construction of east wall of Mill A wheel-pit area.
528	Above Mill A wheel pit.
558	Upper dressing floor.
565	Upper dressing floor.
718	From outside Mill B at southern edge of trench (i.e. downstream edge of trench).
756	Mill A, below stone flooring on south side of furnace. Early smelting phase.
773	Under floor slab of Mill A on west side.
774	Under floor slab of Mill A on west side.
798	Mill A furnace area. Associated with piece of pot c. AD 1600.
901	Openwork trench. At considerable depth in fill. Relates to phase soon after abandonment of openwork?
969	Fill of other pits in Mill B.
970	Fill of stamps pit in Mill B.
978	Fill of most recent stamps pit in Mill B.
979	Fill of stamps pit in Mill B.
993	Stamps area of Mill B
1509	Furnace area of Mill A
1512	Early phase associated with metal found at base of furnace.
1527	Under furnace stone (latest phase) in Mill A

Appendix 4: Composition of Tin Slags determined by EDX-SEM (wt%)

Avon Dam 2/20

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.7	2.9	2.9	2.7	2.6	2.6	2.7	0.1
MgO	3.7	3.8	3.8	3.7	3.5	3.9	3.7	0.1
Al_2O_3	16.4	17.2	17.1	16.7	16.1	16.9	16.7	0.4
SiO_2	42.2	44.5	43.6	42.4	41.9	44.0	43.1	1.1
P_2O_5	0.6	0.4	0.3	0.5	0.6	0.4	0.5	0.1
K_2O	1.9	2.1	1.9	1.9	1.8	2.0	1.9	0.1
CaO	1.1	1.3	1.2	1.2	1.1	1.2	1.2	0.1
TiO_2	8.0	8.4	8.2	7.5	8.0	8.0	8.0	0.3
V_2O_5	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.1
MnO	0.5	0.5	0.4	0.4	0.5	0.4	0.5	0.1
FeO	9.5	8.8	9.1	9.8	9.3	9.0	9.3	0.4
CuO	0.1	nd	0.2	nd	nd	nd	0.1	0.1
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.6	1.8	1.6	1.6	1.5	1.8	1.7	0.1
MoO_3	nd	nd	nd	nd	nd	nd	nd	-
SnO	11.6	8.9	10.5	11.1	12.9	10.9	11.0	1.3
Sb_2O_3	0.1	0.2	0.1	nd	0.1	0.1	0.1	0.1
WO_3	0.7	0.3	0.1	0.9	0.8	nd	0.5	0.3
Sum	101.0	101.5	101.3	100.8	101.1	101.5	101.3	

Blackaller 4/22

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	3.1	3.0	3.5	3.7	3.5	4.3	3.5	0.5
MgO	3.7	3.9	3.4	3.6	3.6	4.0	3.7	0.2
Al_2O_3	21.0	20.6	20.8	20.8	21.6	21.5	21.1	0.4
SiO_2	42.4	41.5	41.9	41.9	43.4	43.5	42.4	0.8
P_2O_5	0.5	0.4	0.3	0.2	0.5	0.2	0.4	0.1
K_2O	2.7	2.6	2.5	2.5	2.9	2.8	2.7	0.2
CaO	2.4	2.4	2.4	2.3	2.5	2.5	2.4	0.1
TiO_2	2.9	2.7	2.6	2.8	2.8	2.8	2.8	0.1
V_2O_5	0.2	0.1	nd	0.1	0.1	0.3	0.1	0.1
MnO	0.2	0.3	0.3	0.3	0.3	0.4	0.3	0.1
FeO	14.1	14.5	14.3	14.3	14.7	14.7	14.4	0.2
CuO	nd	nd	nd	nd	0.1	0.1	0.0	0.1
ZnO	nd	nd	0.2	nd	0.2	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	0.2	0.1	nd	0.1	0.1	0.1
MoO_3	nd	0.1	0.2	0.1	0.3	0.1	0.1	0.1
SnO	7.7	9.0	8.2	8.1	8.5	8.3	8.3	0.4
Sb_2O_3	0.4	0.4	nd	nd	0.1	nd	0.2	0.2
WO_3	0.2	0.2	0.5	0.7	0.7	0.8	0.5	0.3
Sum	101.5	101.7	101.3	101.5	105.8	106.5	103.1	

nd = not detected

Butterbrook 2/33

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.4	2.0	2.5	2.2	2.1	2.4	2.3	0.2
MgO	3.4	3.4	3.3	3.0	3.2	3.2	3.3	0.2
Al_2O_3	15.8	16.5	16.6	15.5	15.6	15.8	16.0	0.5
SiO_2	37.2	38.5	37.9	36.7	37.5	37.1	37.5	0.6
P_2O_5	0.5	0.5	0.4	0.3	0.4	0.5	0.4	0.1
K_2O	1.2	1.3	1.3	1.4	1.4	1.2	1.3	0.1
CaO	0.9	0.7	0.7	0.7	0.8	0.8	0.8	0.1
TiO_2	6.3	6.1	5.4	6.5	6.2	6.2	6.1	0.4
V_2O_5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
MnO	0.5	0.4	0.5	0.4	0.5	0.6	0.5	0.1
FeO	12.9	12.7	13.2	14.4	14.9	13.0	13.5	0.9
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.2	0.9	1.2	1.1	0.9	1.2	1.1	0.1
MoO_3	0.1	nd	nd	nd	0.1	0.1	0.1	0.1
SnO	17.1	17.3	16.9	16.7	16.3	17.4	17.0	0.4
Sb_2O_3	0.2	nd	nd	0.2	0.2	0.2	0.1	0.1
WO_3	1.5	0.4	1.1	1.5	1.1	1.0	1.1	0.3
Sum	101.4	100.9	101.2	100.8	101.4	101.0	101.1	

Butterbrook 2/34

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	1.8	1.8	2.0	1.5	2.0	1.8	0.2
MgO	2.4	2.4	2.5	2.4	2.6	2.5	2.5	0.1
Al_2O_3	14.0	14.3	14.0	14.4	14.1	13.9	14.1	0.2
SiO_2	35.0	35.8	35.5	35.7	35.8	35.3	35.5	0.3
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.9	1.9	1.9	1.8	1.8	1.9	1.9	0.1
CaO	0.8	0.9	0.9	1.0	0.9	1.0	0.9	0.1
TiO_2	7.7	7.5	7.9	7.6	7.7	7.8	7.7	0.1
V_2O_5	0.2	0.2	0.2	nd	0.3	0.2	0.2	0.1
MnO	0.7	0.7	0.8	0.7	0.8	0.7	0.7	0.1
FeO	23.3	23.2	23.3	23.3	23.9	23.4	23.4	0.3
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.2	nd	nd	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.9	1.1	1.0	1.0	0.9	1.0	1.0	0.1
MoO_3	0.3	0.3	0.2	0.2	0.2	0.4	0.3	0.1
SnO	7.4	7.5	7.6	7.6	7.6	7.8	7.6	0.1
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	-
WO_3	4.0	3.0	3.4	3.2	2.9	3.4	3.3	0.4
Sum	100.6	100.6	101.0	100.9	101.0	101.2	100.9	

Caerloggas 3/44

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.3	1.4	1.6	1.2	1.2	1.4	0.2
MgO	2.3	1.8	2.0	2.0	1.9	1.9	2.0	0.2
Al_2O_3	15.0	13.8	14.0	13.7	13.5	14.0	14.0	0.5
SiO_2	27.4	25.4	24.8	24.4	24.2	25.7	25.3	1.2
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.0	0.8	0.7	0.8	0.7	1.0	0.8	0.1
CaO	0.9	0.5	0.9	0.6	0.8	0.9	0.8	0.2
TiO_2	1.7	1.6	1.7	1.5	1.3	1.7	1.6	0.2
V_2O_5	0.1	0.1	0.1	0.3	0.2	nd	0.1	0.1
MnO	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.0
FeO	5.6	5.1	5.2	5.2	5.0	5.6	5.3	0.3
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	0.1	0.1	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.5	0.2	0.5	0.3	0.4	0.5	0.4	0.1
MoO_3	0.1	nd	0.6	0.1	0.1	0.3	0.2	0.2
SnO	40.2	45.3	44.8	46.1	48.3	42.5	44.5	2.8
Sb_2O_3	0.3	0.9	nd	nd	nd	0.5	0.3	0.4
WO_3	3.8	3.6	3.6	3.6	2.9	4.4	3.7	0.5
Sum	101.0	100.9	100.8	100.7	101.1	100.7	100.9	

Caerloggas 3/45

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	1.6	1.3	1.8	1.6	1.7	1.6	0.2
MgO	2.1	2.6	2.4	2.5	2.3	2.5	2.4	0.2
Al_2O_3	14.9	15.6	15.5	17.2	15.4	15.7	15.7	0.8
SiO_2	27.5	27.7	27.6	30.7	29.3	28.6	28.6	1.3
P_2O_5	nd	nd	nd	0.3	nd	nd	0.1	0.1
K_2O	1.0	0.9	0.7	1.1	1.0	0.9	0.9	0.1
CaO	0.8	0.7	0.7	0.7	0.6	0.8	0.7	0.1
TiO_2	1.6	1.8	1.7	1.9	1.8	1.7	1.8	0.1
V_2O_5	nd	nd	0.1	nd	nd	nd	nd	-
MnO	0.5	0.3	0.6	0.6	0.5	0.5	0.5	0.1
FeO	5.2	5.2	5.3	5.9	5.1	5.2	5.3	0.3
CuO	nd	nd	nd	nd	0.1	0.1	0.0	0.1
ZnO	nd	nd	nd	nd	nd	0.3	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.4	0.3	nd	0.2	0.4	0.3	0.2
MoO_3	nd	0.3	0.1	0.2	nd	0.1	0.1	0.1
SnO	37.9	37.5	36.5	34.7	40.4	38.2	37.5	1.9
Sb_2O_3	0.5	0.1	nd	0.1	nd	0.4	0.2	0.2
WO_3	3.0	3.0	3.0	3.0	3.1	2.9	3.0	0.1
Sum	97.1	97.7	95.8	100.7	101.4	100.0	98.8	

Carvedras 3/30

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	1.8	1.8	1.7	2.1	1.9	1.9	0.1
MgO	1.0	0.9	0.7	1.1	1.2	1.0	1.0	0.2
Al_2O_3	24.2	24.2	24.2	25.9	23.5	27.5	24.9	1.5
SiO_2	52.8	51.4	53.4	51.8	53.5	53.0	52.7	0.9
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	2.4	2.1	2.1	2.1	2.1	2.2	2.2	0.1
CaO	1.4	1.3	1.1	1.3	1.4	1.3	1.3	0.1
TiO_2	2.0	2.0	2.1	2.1	2.0	1.7	2.0	0.1
V_2O_5	0.1	0.1	nd	0.2	0.1	0.1	0.1	0.1
MnO	0.2	0.4	0.3	0.2	0.3	0.3	0.3	0.1
FeO	7.5	7.6	6.9	7.1	7.6	7.1	7.3	0.3
CuO	0.1	0.1	nd	nd	nd	nd	0.0	0.1
ZnO	nd	0.1	nd	0.1	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.5	0.6	0.3	0.2	0.1	nd	0.3	0.2
MoO_3	0.3	0.2	0.1	0.2	0.1	0.1	0.2	0.1
SnO	6.4	7.3	8.5	6.4	6.5	4.6	6.6	1.3
Sb_2O_3	0.3	0.1	nd	0.2	0.1	nd	0.1	0.1
WO_3	0.4	1.3	0.3	0.5	0.8	0.1	0.6	0.4
Sum	101.5	101.4	101.6	101.1	101.5	101.0	101.4	

Charlestown 4/20

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.3	1.0	1.1	2.5	0.9	1.3	0.6
MgO	1.2	0.9	1.1	0.9	1.1	1.1	1.1	0.1
Al_2O_3	14.8	15.1	14.3	14.4	14.3	14.1	14.5	0.4
SiO_2	35.6	38.2	35.3	35.3	42.3	36.6	37.2	2.7
P_2O_5	0.2	0.2	0.1	0.1	nd	0.1	0.1	0.1
K_2O	1.6	1.9	1.6	1.5	1.9	1.6	1.7	0.2
CaO	1.0	1.1	1.0	1.0	0.8	1.1	1.0	0.1
TiO_2	2.6	2.3	2.4	2.7	2.0	2.4	2.4	0.2
V_2O_5	0.2	0.1	0.1	0.1	0.2	nd	0.1	0.1
MnO	nd	0.1	nd	0.2	0.1	0.2	0.1	0.1
FeO	27.5	24.2	27.4	27.5	22.4	26.8	26.0	2.2
CuO	nd	nd	0.1	nd	0.1	nd	0.0	0.1
ZnO	0.1	nd	nd	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.4	0.5	0.6	0.7	0.7	0.5	0.2
MoO_3	0.7	0.9	1.5	1.2	0.6	1.3	1.0	0.4
SnO	12.9	12.7	13.4	13.3	12.0	13.5	13.0	0.6
Sb_2O_3	nd	0.3	nd	nd	nd	nd	0.1	0.1
WO_3	2.0	1.3	1.7	1.3	0.4	1.5	1.4	0.5
Sum	101.5	101.0	101.4	101.4	101.4	102.0	101.5	

Crift Farm 4/15

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.2	2.6	3.0	2.4	2.1	3.7	2.7	0.6
MgO	3.3	3.8	4.2	3.7	3.5	3.8	3.7	0.3
Al_2O_3	17.3	17.2	19.4	17.2	17.0	20.7	18.1	1.5
SiO_2	39.0	41.2	43.8	40.0	40.7	42.4	41.2	1.7
P_2O_5	nd	nd	0.2	nd	nd	nd	0.0	0.1
K_2O	1.7	1.7	1.6	1.6	1.8	1.2	1.6	0.2
CaO	1.1	1.2	1.0	1.1	1.2	0.6	1.0	0.2
TiO_2	2.5	2.6	2.6	2.4	3.3	2.0	2.6	0.4
V_2O_5	0.1	0.1	0.1	nd	0.2	0.1	0.1	0.1
MnO	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.1
FeO	8.6	8.7	7.9	8.0	8.9	5.6	8.0	1.2
CuO	nd	nd	nd	nd	0.2	nd	0.0	0.1
ZnO	nd	nd	0.1	0.1	0.3	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.2	0.1	0.2	0.1	0.5	0.3	0.2
MoO_3	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.1
SnO	21.9	19.2	14.9	21.8	18.5	19.9	19.4	2.6
Sb_2O_3	nd	0.1	0.3	nd	0.1	0.1	0.1	0.1
WO_3	2.6	2.1	1.7	2.1	2.6	0.4	1.9	0.7
Sum	101.3	101.4	101.4	101.2	101.1	101.4	101.3	

Crift Farm 4/16

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.4	2.3	2.4	2.5	2.4	2.4	0.1
MgO	4.4	4.3	4.2	4.5	4.1	4.4	4.3	0.1
Al_2O_3	20.7	20.4	20.2	20.1	19.4	20.3	20.2	0.4
SiO_2	42.4	41.2	41.0	42.1	39.9	42.4	41.5	1.0
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.3	1.4	1.4	1.3	1.3	1.4	1.4	0.1
CaO	1.2	1.2	1.0	1.2	1.1	1.2	1.2	0.1
TiO_2	2.1	2.3	2.2	2.3	2.1	2.2	2.2	0.1
V_2O_5	nd	0.1	0.1	0.1	nd	nd	0.1	0.1
MnO	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.0
FeO	5.7	6.0	6.1	6.0	5.8	6.0	5.9	0.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.1	nd	0.1	nd	0.1	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	nd	nd	nd	0.1	0.2	0.2	0.2
MoO_3	0.2	0.1	nd	nd	nd	nd	0.1	0.1
SnO	19.2	19.2	20.1	19.8	21.8	18.6	19.8	1.1
Sb_2O_3	nd	0.3	0.2	nd	0.3	nd	0.1	0.2
WO_3	1.3	2.1	2.2	1.9	2.3	1.8	1.9	0.3
Sum	102.1	101.5	101.5	102.1	101.2	101.3	101.5	

Crift Farm 4/17

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	2.4	2.4	2.3	2.6	2.1	2.3	0.2
MgO	3.4	3.4	3.5	3.3	3.4	3.4	3.4	0.1
Al_2O_3	23.0	25.4	24.2	22.9	24.6	23.5	23.9	1.0
SiO_2	39.6	39.8	39.5	39.0	40.4	39.5	39.6	0.5
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.3	1.4	1.3	1.3	1.3	1.3	1.3	0.0
CaO	1.0	0.9	0.8	0.9	0.8	0.9	0.9	0.1
TiO_2	2.3	2.4	2.3	2.0	2.6	2.4	2.3	0.2
V_2O_5	0.1	0.1	0.1	0.1	nd	0.1	0.1	0.0
MnO	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.0
FeO	6.8	6.8	6.7	7.1	6.7	6.7	6.8	0.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.2	nd	0.1	0.2	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.1	nd	0.6	0.4	0.6	0.4	0.3
MoO_3	0.2	nd	nd	0.2	nd	0.3	0.1	0.1
SnO	18.9	16.9	18.2	18.3	14.9	17.2	17.4	1.4
Sb_2O_3	nd	0.2	nd	nd	nd	nd	0.0	0.1
WO_3	1.5	2.5	1.4	1.4	1.5	1.4	1.6	0.4
Sum	100.9	102.8	100.6	99.8	99.6	99.7	100.6	

Crift Farm 4/27

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.7	2.2	2.1	2.4	2.4	2.8	2.4	0.3
MgO	3.2	3.0	3.3	3.6	3.6	3.3	3.3	0.2
Al_2O_3	19.8	19.8	19.9	20.2	19.7	20.2	19.9	0.2
SiO_2	40.9	41.0	41.0	41.8	41.2	41.6	41.3	0.4
P_2O_5	nd	nd	nd	0.3	0.2	0.2	0.1	0.1
K_2O	1.3	1.3	1.3	1.3	1.3	1.3	1.3	0.0
CaO	1.1	1.3	1.0	1.1	1.0	1.3	1.1	0.1
TiO_2	2.7	2.9	2.8	2.9	2.7	2.8	2.8	0.1
V_2O_5	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1
MnO	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1
FeO	8.6	8.6	8.7	8.2	8.9	8.8	8.6	0.2
CuO	nd	nd	nd	0.1	0.1	nd	0.0	0.1
ZnO	nd	0.1	nd	nd	nd	0.1	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.4	0.3	nd	nd	nd	0.2	0.2
MoO_3	0.1	0.2	0.1	nd	nd	nd	0.1	0.1
SnO	20.3	18.4	19.8	18.6	19.8	17.9	19.1	1.0
Sb_2O_3	nd	0.6	0.1	0.2	nd	0.1	0.2	0.2
WO_3	0.3	1.1	0.5	0.5	0.3	1.2	0.7	0.4
Sum	101.6	101.1	101.2	101.5	101.4	101.8	101.4	

Ditsworthy 3/01

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.5	1.5	1.6	1.7	1.5	2.0	1.6	0.2
MgO	1.8	1.6	1.6	1.7	1.6	1.8	1.7	0.1
Al_2O_3	14.0	13.2	14.2	13.7	13.9	14.0	13.8	0.4
SiO_2	35.1	33.4	35.0	34.1	34.5	34.6	34.5	0.6
P_2O_5	0.1	0.2	0.2	0.1	nd	0.1	0.1	0.1
K_2O	2.7	2.6	2.6	2.6	2.6	2.6	2.6	0.0
CaO	2.2	2.0	1.9	1.9	1.9	1.9	2.0	0.1
TiO_2	6.0	5.8	6.0	6.1	5.9	6.1	6.0	0.1
V_2O_5	0.2	0.3	0.2	0.1	0.3	0.1	0.2	0.1
MnO	0.4	0.5	0.4	0.4	0.5	0.4	0.4	0.1
FeO	8.7	8.2	8.4	8.2	8.5	8.3	8.4	0.2
CuO	nd	nd	nd	0.1	nd	nd	0.0	0.0
ZnO	nd	nd	0.2	nd	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.7	0.6	0.6	0.7	1.0	0.5	0.7	0.2
MoO_3	nd	0.3	0.2	nd	0.2	nd	0.1	0.1
SnO	26.9	30.4	27.2	29.2	28.4	27.9	28.3	1.3
Sb_2O_3	0.1	0.1	nd	nd	nd	0.1	0.1	0.1
WO_3	0.6	0.3	0.2	0.2	0.4	nd	0.3	0.2
Sum	101.0	101.0	100.5	100.8	101.2	100.5	100.8	

Doe Tor Green 2/12

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.2	2.4	2.4	2.3	2.4	2.4	0.1
MgO	3.5	3.3	3.5	3.6	3.2	3.2	3.4	0.2
Al_2O_3	15.6	15.4	15.8	15.9	15.6	15.3	15.6	0.2
SiO_2	41.0	40.0	41.6	42.0	41.6	40.9	41.2	0.7
P_2O_5	0.3	0.3	nd	0.4	0.4	0.6	0.3	0.2
K_2O	1.5	1.5	1.5	1.5	1.6	1.5	1.5	0.0
CaO	0.6	0.7	0.8	0.7	0.7	0.5	0.7	0.1
TiO_2	7.6	7.3	8.0	7.7	7.7	7.6	7.7	0.2
V_2O_5	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.1
MnO	0.8	0.7	0.9	0.7	0.7	0.7	0.8	0.1
FeO	10.9	11.1	10.7	10.7	11.3	11.1	11.0	0.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	0.1	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	4.7	4.3	5.1	4.6	4.5	4.3	4.6	0.3
MoO_3	0.2	0.1	0.1	nd	nd	0.1	0.1	0.1
SnO	10.9	13.4	8.8	9.5	10.9	11.2	10.8	1.6
Sb_2O_3	0.1	nd	0.1	nd	nd	nd	0.0	0.1
WO_3	1.0	1.1	1.3	1.2	1.1	1.1	1.1	0.1
Sum	101.4	101.5	100.9	101.0	101.7	100.7	101.2	

Drakeford Bridge 2/19

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.0	1.8	2.0	2.1	2.0	2.0	0.1
MgO	1.5	1.4	1.4	1.3	1.2	1.2	1.3	0.1
Al_2O_3	11.1	11.0	11.3	11.0	10.9	10.9	11.0	0.2
SiO_2	31.6	31.2	32.0	30.7	29.6	31.2	31.1	0.8
P_2O_5	0.3	0.4	0.2	0.2	0.1	0.2	0.2	0.1
K_2O	3.1	3.3	3.3	3.1	3.1	3.3	3.2	0.1
CaO	2.4	2.3	2.1	2.1	2.0	2.1	2.2	0.2
TiO_2	10.2	10.1	10.4	10.2	11.0	10.3	10.4	0.3
V_2O_5	0.1	0.3	0.3	0.2	0.2	0.2	0.2	0.1
MnO	0.9	0.7	0.6	0.7	0.6	0.8	0.7	0.1
FeO	24.7	25.4	26.0	26.3	28.0	26.1	26.1	1.1
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.1	0.1	nd	nd	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	0.5	0.6	0.7	0.7	0.7	0.6	0.1
MoO_3	0.1	0.1	0.2	0.1	0.2	nd	0.1	0.1
SnO	11.1	10.8	9.9	11.1	10.4	10.3	10.6	0.5
Sb_2O_3	0.3	0.3	nd	0.1	0.1	0.2	0.2	0.1
WO_3	0.6	0.9	0.6	0.7	0.5	1.1	0.7	0.2
Sum	100.6	100.8	100.7	100.5	100.7	100.7	100.6	

Eylesbarrow 2/35

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.4	2.2	2.5	2.5	3.2	2.6	0.3
MgO	1.4	1.1	1.3	1.5	1.2	0.9	1.2	0.2
Al_2O_3	21.9	22.0	21.5	21.9	22.8	22.6	22.1	0.5
SiO_2	48.7	52.3	48.3	46.3	50.5	51.1	49.5	2.2
P_2O_5	0.3	0.3	nd	nd	nd	nd	0.1	0.2
K_2O	3.8	3.9	2.8	3.5	4.0	4.3	3.7	0.5
CaO	3.2	2.8	2.8	2.4	2.8	2.9	2.8	0.3
TiO_2	1.7	1.7	2.0	1.9	2.0	1.9	1.9	0.1
V_2O_5	nd	nd	0.1	nd	0.1	0.1	0.1	0.1
MnO	nd	0.1	nd	nd	0.2	0.1	0.1	0.1
FeO	14.2	11.2	14.5	15.9	11.8	10.9	13.1	2.1
CuO	nd	nd	nd	nd	0.1	nd	0.0	0.0
ZnO	nd	nd	0.2	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	nd	0.4	0.2	0.2	0.1	0.2
MoO_3	0.1	0.2	nd	0.3	0.1	0.2	0.2	0.1
SnO	3.5	3.7	5.1	4.6	3.3	3.1	3.9	0.8
Sb_2O_3	0.1	nd	nd	0.3	nd	nd	0.1	0.1
WO_3	nd	nd	0.1	nd	nd	nd	0.0	0.0
Sum	101.4	101.7	100.9	101.5	101.6	101.5	101.4	

Eylesbarrow 4/05

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.2	1.4	1.3	1.6	1.3	1.4	0.2
MgO	1.0	1.1	0.7	0.8	0.9	0.7	0.9	0.2
Al_2O_3	27.2	30.2	27.4	30.1	30.6	33.2	29.8	2.2
SiO_2	61.9	58.6	63.3	60.8	59.1	57.6	60.2	2.2
P_2O_5	nd	nd	nd	nd	0.1	nd	0.0	0.0
K_2O	2.9	2.8	2.8	3.1	2.8	2.6	2.8	0.2
CaO	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.1
TiO_2	2.1	1.8	1.6	1.7	1.8	1.8	1.8	0.2
V_2O_5	0.1	nd	0.1	0.1	nd	nd	0.1	0.1
MnO	0.1	0.1	nd	nd	nd	0.1	0.1	0.1
FeO	4.3	4.8	3.5	4.1	4.5	4.5	4.3	0.4
CuO	nd	nd	nd	nd	0.2	nd	0.0	0.1
ZnO	0.1	nd	0.1	nd	0.2	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	nd	nd	nd	nd	nd	-
MoO_3	0.2	nd	nd	nd	nd	nd	0.0	0.1
SnO	nd	0.1	0.1	nd	nd	nd	0.0	0.1
Sb_2O_3	nd	0.1	0.1	nd	nd	nd	0.0	0.1
WO_3	nd	0.4	nd	nd	0.1	nd	0.1	0.2
Sum	101.9	101.6	101.4	102.4	102.3	102.1	102.0	

Eylesbarrow 4/06

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.2	1.9	1.7	1.6	1.1	1.9	1.6	0.3
MgO	0.3	0.2	0.6	0.5	0.4	0.6	0.4	0.2
Al_2O_3	22.9	39.4	21.1	27.1	34.9	20.0	27.6	7.9
SiO_2	59.9	47.3	56.3	54.6	49.0	58.2	54.2	5.1
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.6	0.8	1.4	1.3	0.9	1.5	1.3	0.3
CaO	0.6	0.4	0.9	0.5	0.5	0.7	0.6	0.2
TiO_2	0.8	0.6	0.8	0.8	0.7	0.9	0.8	0.1
V_2O_5	nd	nd	nd	nd	0.1	nd	0.0	0.0
MnO	nd	nd	0.1	0.1	nd	0.1	0.1	0.1
FeO	6.5	4.5	10.7	7.5	5.3	6.7	6.9	2.2
CuO	nd	0.1	0.1	nd	nd	0.1	0.1	0.1
ZnO	nd	nd	0.1	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	nd	nd	nd	nd	nd	-
MoO_3	0.4	nd	0.1	0.1	nd	nd	0.1	0.2
SnO	6.7	5.9	7.2	6.1	5.8	7.9	6.6	0.8
Sb_2O_3	nd	nd	nd	0.1	0.1	nd	0.0	0.1
WO_3	0.4	nd	nd	0.5	nd	nd	0.2	0.2
Sum	101.3	101.1	101.1	100.8	98.8	98.6	100.3	

Glazebrook 2/58

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.1	1.9	2.1	1.8	1.5	1.9	0.2
MgO	3.4	3.1	3.0	3.0	3.0	2.6	3.0	0.3
Al_2O_3	18.1	18.0	17.7	17.9	17.7	16.6	17.7	0.5
SiO_2	38.6	37.2	37.9	38.2	37.7	35.1	37.5	1.2
P_2O_5	0.2	0.1	0.1	0.2	0.1	nd	0.1	0.1
K_2O	1.3	1.3	1.3	1.3	1.3	1.3	1.3	0.0
CaO	1.0	1.1	1.1	1.0	1.0	1.0	1.0	0.1
TiO_2	6.3	6.9	6.7	6.4	6.4	6.9	6.6	0.3
V_2O_5	0.2	0.1	0.3	0.1	0.1	0.4	0.2	0.1
MnO	0.6	0.7	0.8	0.7	0.5	0.5	0.6	0.1
FeO	16.9	16.9	17.5	17.0	17.2	18.3	17.3	0.5
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	0.1	0.1	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	0.6	0.7	0.7	0.6	1.0	0.7	0.2
MoO_3	0.2	0.2	0.1	0.3	0.2	0.2	0.2	0.1
SnO	9.2	10.4	9.5	9.7	10.1	12.6	10.1	1.4
Sb_2O_3	nd	nd	nd	0.1	nd	0.1	0.0	0.1
WO_3	2.5	2.5	2.6	2.2	2.7	2.7	2.5	0.2
Sum	101.0	101.2	101.2	101.0	100.5	100.8	100.9	

Gobbett 2/28

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	2.5	1.7	1.8	2.0	1.7	2.0	0.3
MgO	2.8	3.0	3.0	2.9	3.1	2.7	2.9	0.1
Al_2O_3	12.4	13.3	13.1	13.1	13.5	13.5	13.2	0.4
SiO_2	33.9	36.6	36.2	35.8	35.8	36.3	35.8	1.0
P_2O_5	0.2	nd	0.2	0.2	0.1	0.3	0.2	0.1
K_2O	1.2	1.3	1.4	1.3	1.3	1.2	1.3	0.1
CaO	0.6	0.7	0.7	0.6	0.7	0.7	0.7	0.1
TiO_2	6.4	8.2	6.3	6.6	6.7	6.5	6.8	0.7
V_2O_5	nd	0.1	0.2	0.1	0.1	0.2	0.1	0.1
MnO	0.5	0.4	0.5	0.6	0.5	0.6	0.5	0.1
FeO	15.3	16.3	15.4	16.0	15.7	15.6	15.7	0.4
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	nd	0.1	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.6	0.6	0.7	0.9	0.4	0.6	0.2
MoO_3	nd	nd	0.2	0.2	0.2	nd	0.1	0.1
SnO	19.6	20.0	20.5	20.6	20.1	20.6	20.2	0.4
Sb_2O_3	0.4	0.2	0.1	nd	nd	nd	0.1	0.2
WO_3	0.6	0.6	1.0	0.5	0.5	0.7	0.7	0.2
Sum	96.4	103.8	101.3	101.0	101.2	101.0	100.8	

Hurdon 2/01

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.3	1.0	1.0	1.1	0.9	1.1	0.1
MgO	2.5	2.7	2.3	2.6	2.5	2.3	2.5	0.2
Al_2O_3	10.7	10.7	10.2	11.0	10.5	10.1	10.5	0.3
SiO_2	29.6	29.5	28.3	30.5	29.3	28.2	29.2	0.9
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.5	1.5	1.4	1.7	1.4	1.4	1.5	0.1
CaO	2.2	2.3	2.4	2.5	2.3	2.2	2.3	0.1
TiO_2	4.8	4.8	4.7	5.2	4.7	4.7	4.8	0.2
V_2O_5	0.2	0.1	0.1	nd	0.1	0.1	0.1	0.1
MnO	2.1	2.2	2.1	2.3	2.2	2.0	2.2	0.1
FeO	9.8	9.9	9.8	9.9	9.8	9.5	9.8	0.1
CuO	nd	nd	nd	0.1	nd	0.1	0.0	0.1
ZnO	nd	0.1	nd	nd	nd	0.1	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.3	1.9	2.2	1.6	2.2	2.1	2.1	0.3
MoO_3	1.2	0.9	1.2	0.8	0.9	1.1	1.0	0.2
SnO	19.5	18.9	21.0	18.3	21.3	21.0	20.0	1.3
Sb_2O_3	nd	0.5	0.6	0.1	0.3	0.6	0.4	0.3
WO_3	15.1	15.2	14.9	14.6	14.3	15.7	15.0	0.4
Sum	102.5	102.5	102.2	102.2	102.9	102.1	102.4	

Hurdon 4/26

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.1	0.9	1.0	0.9	1.0	1.0	0.1
MgO	1.4	1.5	1.5	1.4	1.2	1.2	1.4	0.1
Al_2O_3	10.9	11.1	11.3	11.3	10.6	10.4	10.9	0.4
SiO_2	31.5	31.5	31.6	31.3	29.0	29.6	30.8	1.1
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.2	1.4	1.3	1.4	1.0	1.3	1.3	0.2
CaO	0.7	0.5	0.6	0.6	0.5	0.6	0.6	0.1
TiO_2	3.7	3.6	3.6	3.6	3.6	3.4	3.6	0.1
V_2O_5	0.2	0.1	0.1	0.1	nd	nd	0.1	0.1
MnO	3.1	3.0	3.1	3.1	3.1	2.8	3.0	0.1
FeO	7.9	8.0	7.8	7.9	7.9	7.7	7.9	0.1
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	0.1	0.2	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.3	2.4	2.5	2.3	2.7	2.3	2.4	0.2
MoO_3	1.4	1.5	1.2	1.2	1.3	1.2	1.3	0.1
SnO	21.5	21.3	21.4	21.9	25.5	25.1	22.8	2.0
Sb_2O_3	0.3	0.3	0.4	0.2	nd	0.2	0.2	0.1
WO_3	15.8	16.1	15.5	15.4	15.4	15.2	15.6	0.3
Sum	102.9	103.4	103.8	102.7	102.8	102.2	102.9	

Lether Tor Farm 2/11

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.0	1.8	1.7	2.2	1.9	1.6	1.9	0.2
MgO	4.4	4.0	4.1	4.4	4.0	4.2	4.2	0.2
Al_2O_3	14.5	14.5	14.4	15.1	14.6	14.0	14.5	0.4
SiO_2	38.6	38.8	38.0	40.2	39.3	37.4	38.7	1.0
P_2O_5	0.2	0.4	0.6	0.3	0.3	0.3	0.4	0.1
K_2O	1.6	1.6	1.6	1.7	1.7	1.6	1.6	0.1
CaO	0.3	0.5	0.4	0.5	0.5	0.4	0.4	0.1
TiO_2	4.5	5.1	5.0	4.1	4.3	4.6	4.6	0.4
V_2O_5	0.1	0.2	0.1	0.1	0.2	nd	0.1	0.1
MnO	0.4	0.4	0.5	0.4	0.5	0.4	0.4	0.1
FeO	8.4	9.2	9.8	8.7	8.8	8.5	8.9	0.5
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	0.1	nd	nd	0.1	0.2	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.5	0.5	0.4	0.4	0.5	0.6	0.5	0.1
MoO_3	0.2	nd	nd	nd	nd	0.2	0.1	0.1
SnO	26.0	24.7	24.6	23.4	24.7	27.4	25.1	1.4
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	-
WO_3	0.4	0.2	0.5	0.7	0.4	0.5	0.5	0.2
Sum	102.2	101.9	101.7	102.3	101.9	101.9	102.0	

Lingcombe 3/19

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.6	2.5	2.5	2.5	2.6	2.5	0.1
MgO	3.1	3.4	3.3	3.5	3.7	3.6	3.4	0.2
Al_2O_3	17.8	17.2	17.7	17.5	17.5	18.2	17.7	0.3
SiO_2	42.3	41.7	42.0	41.3	41.0	43.6	42.0	0.9
P_2O_5	0.9	1.3	1.0	1.2	1.4	1.0	1.1	0.2
K_2O	2.8	2.8	2.8	2.7	2.7	2.9	2.8	0.1
CaO	1.9	2.0	1.9	1.9	2.0	2.0	2.0	0.1
TiO_2	7.0	7.0	7.1	6.9	6.9	7.3	7.0	0.2
V_2O_5	nd	0.1	nd	nd	0.1	0.1	0.1	0.1
MnO	0.4	0.4	0.6	0.5	0.5	0.4	0.5	0.1
FeO	14.3	14.6	14.1	14.9	14.6	13.7	14.4	0.4
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	nd	nd	nd	nd	0.1	0.2	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	nd	nd	0.1	nd	nd	0.1	0.1
MoO_3	0.2	0.2	0.1	0.2	0.1	nd	0.1	0.1
SnO	7.1	7.0	6.9	8.0	8.0	5.7	7.1	0.9
Sb_2O_3	nd	0.2	0.2	0.1	0.1	nd	0.1	0.1
WO_3	0.3	0.3	0.7	0.1	0.6	0.1	0.3	0.2
Sum	100.9	100.8	100.9	101.4	101.8	101.5	101.2	

Lingcombe 3/20

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.0	2.8	2.4	1.9	1.6	2.1	2.1	0.4
MgO	1.3	1.2	1.1	1.3	1.5	1.3	1.3	0.1
Al_2O_3	10.9	11.6	11.3	11.2	10.6	10.8	11.1	0.4
SiO_2	35.3	39.2	38.5	38.2	35.8	35.9	37.2	1.7
P_2O_5	nd	nd	nd	0.1	nd	0.1	0.0	0.1
K_2O	2.4	2.9	3.0	2.6	2.8	2.8	2.8	0.2
CaO	1.9	1.9	1.8	2.2	1.8	1.8	1.9	0.2
TiO_2	11.1	8.1	7.9	7.5	9.2	9.2	8.8	1.3
V_2O_5	0.1	0.1	0.1	nd	0.1	0.2	0.1	0.1
MnO	1.0	0.9	1.0	1.0	1.0	1.1	1.0	0.1
FeO	25.0	23.1	23.3	22.4	26.3	26.0	24.4	1.6
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.1	nd	0.2	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.3	1.1	1.4	1.4	0.9	1.0	1.2	0.2
MoO_3	nd	nd	0.1	0.2	nd	0.1	0.1	0.1
SnO	8.2	7.9	8.6	9.6	8.3	7.9	8.4	0.6
Sb_2O_3	0.2	nd	nd	nd	0.2	nd	0.1	0.1
WO_3	0.1	0.3	0.2	1.0	0.8	0.4	0.5	0.4
Sum	100.8	101.2	100.7	100.8	100.9	100.8	100.9	

Longstone 2/06

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.3	2.2	1.9	2.0	1.7	2.0	0.2
MgO	3.2	4.0	3.2	3.3	3.3	3.3	3.4	0.3
Al_2O_3	13.6	17.0	14.5	14.2	14.1	14.2	14.6	1.2
SiO_2	35.0	42.6	37.1	36.2	35.9	35.9	37.1	2.8
P_2O_5	0.3	0.2	0.1	0.3	0.2	0.1	0.2	0.1
K_2O	1.2	1.4	1.4	1.4	1.3	1.4	1.4	0.1
CaO	0.8	0.6	0.7	0.6	0.6	0.6	0.7	0.1
TiO_2	2.7	3.1	2.7	2.8	2.6	2.8	2.8	0.2
V_2O_5	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1
MnO	0.2	0.4	0.2	0.2	0.2	0.3	0.3	0.1
FeO	7.2	8.3	7.4	7.1	7.2	7.1	7.4	0.5
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.9	0.9	0.9	1.0	0.8	1.0	0.9	0.1
MoO_3	nd	nd	nd	nd	nd	nd	nd	-
SnO	33.3	19.2	30.3	30.9	32.7	32.7	29.9	5.3
Sb_2O_3	0.3	0.1	0.2	nd	0.4	0.2	0.2	0.1
WO_3	0.5	0.8	nd	0.6	nd	nd	0.3	0.3
Sum	101.3	101.0	101.1	100.6	101.4	101.5	101.1	

Longstone 2/07

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	1.9	1.9	2.2	1.9	1.8	1.9	0.1
MgO	3.1	3.1	3.3	3.2	3.0	3.1	3.1	0.1
Al_2O_3	13.6	14.0	14.3	14.3	13.6	14.0	14.0	0.3
SiO_2	35.1	36.1	35.9	36.6	34.2	35.6	35.6	0.8
P_2O_5	0.1	0.3	0.2	0.3	0.1	0.2	0.2	0.1
K_2O	1.2	1.3	1.3	1.2	1.2	1.2	1.2	0.1
CaO	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.0
TiO_2	2.6	2.7	2.8	2.6	2.5	2.5	2.6	0.1
V_2O_5	0.1	0.2	0.1	0.1	0.1	nd	0.1	0.1
MnO	0.2	0.2	0.3	0.2	0.2	0.1	0.2	0.1
FeO	7.0	6.7	6.9	6.8	6.7	6.7	6.8	0.1
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.3	nd	nd	0.1	nd	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.7	0.6	0.9	0.7	0.9	0.8	0.8	0.1
MoO_3	nd	nd	nd	0.1	0.1	0.1	0.1	0.1
SnO	31.9	30.4	29.4	29.5	34.3	29.7	30.9	1.9
Sb_2O_3	0.2	0.4	0.5	0.4	0.6	0.2	0.4	0.2
WO_3	0.9	0.4	0.6	0.2	0.2	0.4	0.5	0.3
Sum	99.4	98.8	98.9	99.0	100.1	96.8	98.8	

Longstone 2/47

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.4	1.8	2.3	2.2	2.0	2.3	2.2	0.2
MgO	3.6	3.4	3.6	3.5	3.5	3.3	3.5	0.1
Al_2O_3	19.8	19.3	18.8	18.7	19.0	18.7	19.1	0.4
SiO_2	43.7	43.4	42.5	42.1	42.4	42.1	42.7	0.7
P_2O_5	0.7	0.6	0.7	0.8	0.7	0.8	0.7	0.1
K_2O	1.5	1.4	1.5	1.3	1.3	1.3	1.4	0.1
CaO	1.7	1.6	1.5	1.5	1.4	1.3	1.5	0.1
TiO_2	2.0	2.0	2.0	2.0	2.0	1.9	2.0	0.0
V_2O_5	nd	nd	nd	0.1	nd	nd	0.0	0.0
MnO	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.0
FeO	16.0	16.6	16.4	17.4	16.9	16.8	16.7	0.5
CuO	nd	nd	0.2	nd	nd	nd	0.0	0.1
ZnO	nd	0.1	nd	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	0.1	nd	nd	0.1	nd	0.0	0.1
MoO_3	0.1	0.1	nd	nd	nd	nd	0.0	0.1
SnO	9.1	10.7	11.0	11.8	11.5	11.8	11.0	1.0
Sb_2O_3	0.1	0.2	nd	nd	nd	0.1	0.1	0.1
WO_3	0.3	nd	0.5	nd	nd	0.2	0.2	0.2
Sum	101.2	101.5	101.3	101.6	101.0	100.8	101.3	

Longstone 4/24

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.0	2.0	1.6	1.4	2.1	1.8	1.8	0.3
MgO	2.4	2.5	2.7	2.3	2.6	2.4	2.5	0.1
Al_2O_3	13.2	13.2	12.7	12.5	13.3	13.3	13.0	0.3
SiO_2	35.1	34.5	33.2	33.6	35.0	34.4	34.3	0.8
P_2O_5	0.3	0.3	0.5	0.5	0.5	0.5	0.4	0.1
K_2O	1.1	1.0	0.8	0.9	0.9	1.0	1.0	0.1
CaO	0.5	0.4	0.5	0.5	0.4	0.4	0.5	0.1
TiO_2	4.6	4.4	4.2	4.2	4.3	4.1	4.3	0.2
V_2O_5	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1
MnO	0.3	0.2	0.4	0.2	0.3	0.3	0.3	0.1
FeO	7.1	6.7	6.8	6.7	6.9	6.6	6.8	0.2
CuO	Nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	0.1	nd	nd	nd	0.1	nd	0.0	0.1
As_2O_3	Nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.4	0.2	0.1	0.1	0.1	0.2	0.1
MoO_3	0.2	0.1	0.2	0.1	0.1	nd	0.1	0.1
SnO	32.3	34.6	37.2	37.6	34.4	35.6	35.3	2.0
Sb_2O_3	0.3	0.1	0.2	nd	nd	nd	0.1	0.1
WO_3	0.5	nd	nd	nd	0.2	0.1	0.1	0.2
Sum	100.7	100.8	101.4	100.8	101.4	100.8	101.0	

Lustleigh 2/50

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.5	1.7	1.5	1.3	1.8	1.6	1.6	0.2
MgO	1.5	1.4	1.4	1.3	1.4	1.5	1.4	0.1
Al_2O_3	12.6	12.8	12.6	12.4	12.7	12.3	12.6	0.2
SiO_2	29.6	29.6	28.7	28.6	30.2	28.5	29.2	0.7
P_2O_5	0.1	0.2	0.3	0.4	0.2	nd	0.2	0.1
K_2O	2.5	2.5	2.3	2.5	2.5	2.4	2.5	0.1
CaO	2.4	2.4	2.5	2.4	2.5	2.5	2.5	0.1
TiO_2	10.6	9.9	11.1	11.6	9.5	11.1	10.6	0.8
V_2O_5	0.1	0.1	0.2	0.1	0.2	0.3	0.2	0.1
MnO	2.0	2.0	2.1	2.0	2.0	2.0	2.0	0.0
FeO	25.7	25.8	26.3	26.1	25.5	26.0	25.9	0.3
CuO	nd	nd	nd	nd	0.1	nd	0.0	0.0
ZnO	nd	nd	nd	nd	0.1	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	0.3	0.1	0.1	0.2	0.3	0.2	0.1
MoO_3	nd	0.2	nd	nd	0.1	nd	0.1	0.1
SnO	11.5	11.0	11.4	11.0	11.1	11.7	11.3	0.3
Sb_2O_3	0.1	nd	0.1	nd	nd	0.2	0.1	0.1
WO_3	0.7	0.8	0.1	0.7	0.8	0.5	0.6	0.2
Sum	100.9	100.7	100.7	100.5	100.9	100.9	100.7	

Lustleigh 2/51

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	1.8	2.0	1.6	1.7	1.6	1.8	0.2
MgO	1.5	1.7	1.6	1.7	1.8	1.6	1.7	0.1
Al_2O_3	11.3	11.7	11.7	11.7	11.4	11.6	11.6	0.2
SiO_2	28.8	28.9	28.4	27.8	28.6	28.4	28.5	0.4
P_2O_5	0.4	0.2	0.4	0.4	0.3	0.5	0.4	0.1
K_2O	2.1	2.1	2.1	2.0	2.1	2.1	2.1	0.0
CaO	2.2	2.3	2.1	2.3	2.2	2.1	2.2	0.1
TiO_2	8.4	8.8	9.4	9.4	8.7	8.8	8.9	0.4
V_2O_5	0.1	0.1	0.2	0.3	0.3	0.3	0.2	0.1
MnO	3.6	3.6	3.4	3.6	3.7	3.7	3.6	0.1
FeO	25.9	25.6	26.8	26.8	25.9	26.0	26.2	0.5
CuO	nd	nd	nd	nd	0.1	nd	0.0	0.0
ZnO	nd	nd	nd	nd	nd	0.1	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	0.2	nd	nd	0.1	nd	0.1	0.1
MoO_3	nd	nd	nd	nd	nd	0.2	0.0	0.1
SnO	13.8	12.4	11.2	12.5	13.5	13.5	12.8	1.0
Sb_2O_3	0.2	0.4	0.2	0.3	0.5	nd	0.3	0.2
WO_3	0.2	0.7	0.8	0.2	nd	0.5	0.4	0.3
Sum	100.3	100.5	100.3	100.6	100.9	101.0	100.6	

Lower Merrivale 4/04

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.5	1.6	2.1	1.5	1.8	1.5	1.7	0.2
MgO	2.7	2.8	2.5	2.5	2.3	2.7	2.6	0.2
Al_2O_3	19.0	18.1	18.6	18.0	17.2	18.3	18.2	0.6
SiO_2	40.9	40.0	40.7	39.2	37.7	39.9	39.7	1.2
P_2O_5	0.6	0.6	0.6	0.7	0.5	0.8	0.6	0.1
K_2O	1.2	1.3	1.2	1.3	1.2	1.3	1.3	0.1
CaO	0.9	0.8	0.7	1.0	0.8	0.9	0.9	0.1
TiO_2	2.7	2.9	2.6	2.7	2.6	2.8	2.7	0.1
V_2O_5	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.1
MnO	0.9	1.1	1.0	0.9	1.0	0.9	1.0	0.1
FeO	20.6	20.7	19.8	20.8	22.0	21.3	20.9	0.7
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.1	nd	nd	0.1	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	0.3	0.1	0.2	nd	0.1	0.1
MoO_3	nd	0.2	nd	0.4	0.2	nd	0.1	0.2
SnO	8.7	9.3	10.3	10.4	11.7	10.1	10.1	1.0
Sb_2O_3	nd	0.2	nd	0.2	0.2	0.1	0.1	0.1
WO_3	1.0	1.4	1.1	0.6	1.0	0.3	0.9	0.4
Sum	100.9	101.3	101.6	100.4	100.7	101.1	101.0	

Lower Merrivale 4/28

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.6	2.2	2.2	2.2	2.1	2.5	2.3	0.2
MgO	2.7	2.8	2.6	2.7	2.5	2.7	2.7	0.1
Al_2O_3	18.2	17.9	18.1	17.5	17.7	17.9	17.9	0.3
SiO_2	43.2	43.8	43.8	43.2	44.1	43.7	43.6	0.4
P_2O_5	0.3	0.4	nd	0.2	0.1	0.1	0.2	0.1
K_2O	0.9	0.9	0.8	0.9	1.0	0.8	0.9	0.1
CaO	0.6	0.5	0.5	0.8	0.7	0.6	0.6	0.1
TiO_2	2.0	2.3	2.0	2.2	2.2	2.2	2.2	0.1
V_2O_5	nd	0.2	nd	0.1	0.1	nd	0.1	0.1
MnO	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.1
FeO	13.9	14.9	14.5	14.6	14.4	14.1	14.4	0.4
CuO	nd	nd	0.1	0.1	nd	nd	0.0	0.1
ZnO	nd	nd	nd	nd	0.2	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.1	0.4	0.1	0.2	0.2	0.2	0.1
MoO_3	0.2	0.1	nd	nd	0.2	0.2	0.1	0.1
SnO	17.1	16.5	17.5	16.4	15.6	17.3	16.7	0.7
Sb_2O_3	0.1	nd	nd	0.3	0.1	nd	0.1	0.1
WO_3	0.5	0.3	0.6	0.9	0.8	0.9	0.7	0.2
Sum	102.7	103.2	103.3	102.5	102.2	103.5	102.9	

Upper Merrivale 2/21

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.8	5.9	6.2	2.6	3.7	3.9	1.8
MgO	2.5	2.8	4.3	4.1	2.6	3.2	3.3	0.8
Al_2O_3	16.9	18.9	21.4	21.4	18.6	19.7	19.5	1.7
SiO_2	40.8	44.0	48.9	48.4	43.8	45.7	45.3	3.1
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	2.5	2.3	1.7	1.7	2.4	2.2	2.1	0.4
CaO	1.3	1.2	0.8	0.7	1.1	1.0	1.0	0.2
TiO_2	6.9	5.9	3.3	3.3	6.0	5.4	5.1	1.5
V_2O_5	0.3	0.3	0.2	nd	0.3	0.2	0.2	0.1
MnO	0.8	0.7	0.5	0.4	0.8	0.6	0.6	0.2
FeO	11.5	9.0	4.0	3.6	9.6	7.4	7.5	3.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	0.1	nd	0.1	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.6	2.2	2.0	1.8	1.9	2.3	2.0	0.3
MoO_3	nd	0.3	0.3	0.7	0.3	0.4	0.3	0.2
SnO	13.0	10.5	9.8	10.1	10.2	9.9	10.6	1.2
Sb_2O_3	0.3	nd	0.1	nd	nd	nd	0.1	0.1
WO_3	1.4	1.1	0.2	0.4	1.3	0.9	0.9	0.4
Sum	101.7	102.0	103.5	102.8	101.6	102.6	102.4	

Upper Merrivale 2/22

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.3	1.2	1.3	1.2	1.3	1.3	1.3	0.1
MgO	2.4	2.3	2.4	2.3	2.5	2.5	2.4	0.1
Al_2O_3	12.2	12.0	12.2	12.1	12.8	12.2	12.3	0.3
SiO_2	37.5	37.4	38.2	37.8	39.4	38.0	38.1	0.7
P_2O_5	0.1	0.3	0.2	0.3	0.3	0.3	0.3	0.1
K_2O	1.1	1.1	1.2	1.2	1.1	1.2	1.2	0.1
CaO	0.6	0.7	0.6	0.7	0.6	0.7	0.7	0.1
TiO_2	13.7	14.1	13.8	13.6	12.6	13.3	13.5	0.5
V_2O_5	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.1
MnO	1.1	1.2	1.2	1.3	1.1	1.2	1.2	0.1
FeO	17.4	16.9	16.4	16.7	16.0	16.3	16.6	0.5
CuO	nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	0.1	nd	nd	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.1	0.5	0.3	0.4	0.2	0.3	0.1
MoO_3	0.1	nd	nd	nd	nd	nd	0.0	0.0
SnO	11.5	11.6	10.9	11.8	11.1	11.1	11.3	0.4
Sb_2O_3	nd	0.1	nd	0.2	0.2	0.1	0.1	0.1
WO_3	1.5	1.3	1.7	1.0	1.1	1.9	1.4	0.3
Sum	101.3	100.7	101.0	100.9	100.8	100.6	100.9	

Upper Merrivale 2/23

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.2	2.3	2.1	2.3	2.5	2.2	2.3	0.1
MgO	3.8	4.0	3.9	4.4	4.6	3.6	4.1	0.4
Al_2O_3	14.0	14.9	14.3	15.7	15.8	14.2	14.8	0.8
SiO_2	40.1	42.2	40.8	44.5	44.5	40.6	42.1	2.0
P_2O_5	0.1	0.2	0.2	0.2	0.3	0.1	0.2	0.1
K_2O	1.9	1.9	1.8	2.0	2.0	1.8	1.9	0.1
CaO	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.0
TiO_2	6.1	6.6	6.2	7.2	7.1	6.2	6.6	0.5
V_2O_5	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1
MnO	1.3	1.4	1.4	1.5	1.5	1.2	1.4	0.1
FeO	11.6	11.3	11.5	11.1	10.2	11.3	11.2	0.5
CuO	nd	nd	nd	0.1	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	0.1	0.1	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	3.6	4.0	3.8	4.2	3.9	4.0	3.9	0.2
MoO_3	0.1	0.1	nd	0.1	nd	0.2	0.1	0.1
SnO	12.5	8.7	11.3	6.2	6.6	11.8	9.5	2.7
Sb_2O_3	0.5	nd	0.4	nd	0.1	0.2	0.2	0.2
WO_3	2.4	2.4	2.5	1.1	1.2	2.6	2.0	0.6
Sum	101.1	101.0	101.2	101.5	101.4	101.0	101.2	

Upper Merrivale 2/24

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.7	1.5	1.5	1.5	1.8	1.6	1.6	0.1
MgO	2.7	2.7	2.7	2.7	2.6	2.4	2.6	0.1
Al_2O_3	13.4	13.0	12.8	12.9	12.9	13.1	13.0	0.2
SiO_2	37.5	36.8	35.7	36.3	36.3	36.4	36.5	0.6
P_2O_5	0.3	0.2	0.1	0.1	nd	0.1	0.1	0.1
K_2O	1.1	1.1	0.9	0.8	0.9	0.8	0.9	0.1
CaO	1.0	1.0	1.1	0.9	0.9	0.9	1.0	0.1
TiO_2	3.2	2.9	3.1	3.1	2.9	2.9	3.0	0.1
V_2O_5	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1
MnO	4.0	4.0	4.2	4.0	3.8	4.3	4.1	0.2
FeO	13.3	13.0	12.7	12.5	12.3	13.0	12.8	0.4
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	nd	nd	nd	0.2	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.2	0.2	0.6	0.5	0.2	0.3	0.2
MoO_3	0.2	nd	0.3	0.1	0.1	0.1	0.1	0.1
SnO	22.0	22.4	23.1	22.0	22.2	23.6	22.6	0.7
Sb_2O_3	0.3	nd	0.8	0.3	0.2	0.2	0.3	0.3
WO_3	1.2	0.9	1.1	0.9	0.7	0.7	0.9	0.2
Sum	102.3	99.8	100.4	99.0	98.2	100.6	100.1	

Upper Merrivale 2/25

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.4	1.4	1.2	1.3	1.1	1.0	1.2	0.2
MgO	1.6	1.3	1.7	1.5	1.3	1.5	1.5	0.2
Al_2O_3	10.0	9.3	9.5	9.6	8.9	9.2	9.4	0.4
SiO_2	26.1	24.9	25.2	25.8	23.9	24.5	25.1	0.8
P_2O_5	nd	0.1	nd	nd	nd	nd	0.0	0.0
K_2O	1.0	0.8	0.9	0.9	0.8	0.9	0.9	0.1
CaO	0.6	0.7	0.7	0.6	0.6	0.7	0.7	0.1
TiO_2	6.8	6.3	6.3	6.4	6.2	6.5	6.4	0.2
V_2O_5	0.3	0.2	0.2	0.2	0.1	0.3	0.2	0.1
MnO	0.6	0.4	0.5	0.5	0.6	0.5	0.5	0.1
FeO	10.3	9.6	9.6	9.8	9.5	9.6	9.7	0.3
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	0.1	nd	0.1	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.8	1.7	1.9	2.1	2.1	2.0	1.9	0.2
MoO_3	0.1	nd	0.1	nd	0.2	0.1	0.1	0.1
SnO	38.5	42.3	40.7	40.1	43.2	41.8	41.1	1.7
Sb_2O_3	0.3	0.1	0.5	0.4	0.6	0.6	0.4	0.2
WO_3	1.5	1.3	1.8	1.6	1.6	1.5	1.6	0.2
Sum	101.0	100.4	101.0	100.8	100.7	100.7	100.8	

Upper Merrivale 2/26

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.2	1.5	1.4	1.5	1.4	1.3	1.4	0.1
MgO	3.6	3.2	3.2	3.6	3.8	3.6	3.5	0.2
Al_2O_3	17.3	17.2	16.5	17.9	18.4	17.7	17.5	0.7
SiO_2	36.9	36.1	34.9	37.7	38.0	37.6	36.9	1.2
P_2O_5	0.3	0.3	0.2	0.3	0.4	0.4	0.3	0.1
K_2O	1.1	1.1	1.1	1.1	1.2	1.2	1.1	0.1
CaO	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.0
TiO_2	3.0	2.9	2.8	3.1	3.2	2.8	3.0	0.2
V_2O_5	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.0
MnO	0.5	0.4	0.3	0.4	0.4	0.5	0.4	0.1
FeO	19.4	19.3	20.1	18.8	19.0	19.6	19.4	0.5
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	0.1	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.2	0.3	0.2	0.3	0.3	0.3	0.1
MoO_3	0.3	0.2	0.1	0.3	0.3	0.3	0.3	0.1
SnO	15.1	15.0	16.5	14.1	12.7	12.8	14.4	1.5
Sb_2O_3	nd	0.4	0.4	nd	nd	nd	0.1	0.2
WO_3	1.5	2.2	2.2	1.4	1.3	2.1	1.6	0.4
Sum	101.4	100.9	100.9	101.2	101.3	101.1	101.0	

Upper Merrivale 2/27

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.5	nd	0.2	0.4	0.6	0.4	0.4	0.2
MgO	nd	1.8	2.0	0.9	0.5	0.8	1.0	0.8
Al_2O_3	7.7	8.6	7.8	9.8	6.3	8.1	8.1	1.2
SiO_2	22.3	23.7	24.1	20.9	23.0	22.1	22.7	1.2
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.1	0.4	0.6	0.7	1.0	0.8	0.8	0.3
CaO	0.3	0.2	0.1	0.3	0.4	0.3	0.3	0.1
TiO_2	1.9	1.6	2.1	2.9	2.1	2.4	2.2	0.4
V_2O_5	nd	0.3	0.2	0.1	0.1	0.2	0.2	0.1
MnO	1.0	2.1	2.2	1.6	1.6	1.5	1.7	0.4
FeO	23.5	43.8	42.7	36.7	31.3	32.7	35.1	7.6
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	0.1	nd	0.1	0.0	0.1
As_2O_3	0.2	nd	nd	nd	0.1	0.2	0.1	0.1
ZrO_2	2.2	1.7	1.5	1.7	2.6	2.1	2.0	0.4
MoO_3	1.6	1.0	1.1	0.9	1.4	1.1	1.2	0.3
SnO	29.3	8.2	9.4	15.4	17.9	18.5	16.5	7.6
Sb_2O_3	nd	nd	nd	nd	0.2	nd	0.0	0.1
WO_3	10.8	8.8	7.4	9.0	13.9	10.9	10.1	2.0
Sum	102.4	102.2	101.4	101.4	103.0	102.2	102.0	

Upper Merrivale 2/31

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.8	2.8	3.3	2.6	2.7	2.7	2.8	0.2
MgO	3.9	4.1	3.7	4.0	3.9	4.0	3.9	0.1
Al_2O_3	21.0	20.6	21.1	20.9	20.9	20.8	20.9	0.2
SiO_2	45.1	45.2	45.1	45.6	46.3	46.0	45.6	0.5
P_2O_5	0.4	0.5	0.2	0.6	0.4	0.7	0.5	0.2
K_2O	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.1
CaO	0.6	0.5	0.6	0.5	0.5	0.4	0.5	0.1
TiO_2	1.6	1.5	1.7	1.7	1.6	1.7	1.6	0.1
V_2O_5	0.1	0.1	0.1	nd	0.1	0.1	0.1	0.0
MnO	0.2	0.1	0.3	0.2	0.1	0.2	0.2	0.1
FeO	12.9	12.3	12.4	12.7	12.6	12.6	12.6	0.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.1	0.1	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	0.2	nd	0.2	nd	0.1	0.1
MoO_3	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.1
SnO	11.6	11.9	10.6	10.6	10.8	10.2	11.0	0.7
Sb_2O_3	nd	0.3	nd	0.1	nd	nd	0.1	0.1
WO_3	0.6	0.6	0.9	0.5	0.7	0.8	0.7	0.1
Sum	101.7	101.5	101.3	101.0	101.9	101.4	101.5	

Upper Merrivale 2/32

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.1	1.4	1.5	1.4	1.7	1.5	0.2
MgO	2.4	2.4	2.5	2.4	2.4	2.4	2.4	0.0
Al_2O_3	12.0	12.4	11.9	12.2	12.2	11.4	12.0	0.3
SiO_2	30.4	31.3	30.4	31.1	30.4	29.3	30.5	0.7
P_2O_5	0.1	0.3	nd	0.2	0.1	0.1	0.1	0.1
K_2O	0.8	0.7	0.6	0.7	0.8	0.7	0.7	0.1
CaO	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.0
TiO_2	14.9	14.1	14.3	15.5	15.2	14.6	14.8	0.5
V_2O_5	0.3	0.2	0.3	0.3	0.4	0.2	0.3	0.1
MnO	1.4	1.4	1.4	1.6	1.4	1.3	1.4	0.1
FeO	14.3	14.4	14.9	13.8	14.9	14.8	14.5	0.4
CuO	nd	nd	0.1	nd	0.1	nd	0.0	0.1
ZnO	0.2	nd	0.1	0.1	nd	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	4.4	4.3	4.4	3.9	4.5	4.1	4.3	0.2
MoO_3	0.2	0.2	0.2	nd	nd	0.1	0.1	0.1
SnO	14.7	15.7	15.7	14.5	14.2	16.9	15.3	1.0
Sb_2O_3	nd	nd	0.3	nd	0.1	0.2	0.1	0.1
WO_3	2.7	1.8	1.9	2.8	1.8	2.7	2.3	0.4
Sum	100.9	100.8	100.9	101.0	100.4	101.0	100.8	

Upper Merrivale 2/52

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.3	2.0	1.9	2.5	1.8	2.1	2.1	0.3
MgO	3.8	3.9	3.8	4.3	3.5	3.7	3.8	0.3
Al_2O_3	15.6	16.3	16.3	17.4	15.8	15.8	16.2	0.7
SiO_2	40.4	42.0	41.8	43.9	40.8	41.3	41.7	1.2
P_2O_5	nd	0.1	nd	nd	0.1	nd	0.0	0.1
K_2O	1.2	1.1	1.0	0.9	1.1	1.0	1.1	0.1
CaO	0.6	0.5	0.5	0.5	0.5	0.6	0.5	0.1
TiO_2	6.5	6.4	6.7	5.8	6.9	6.9	6.5	0.4
V_2O_5	0.2	nd	0.1	0.2	0.1	0.1	0.1	0.1
MnO	0.8	0.8	0.8	0.6	0.8	0.9	0.8	0.1
FeO	9.4	8.9	9.5	7.4	9.8	9.6	9.1	0.9
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	3.3	3.1	3.3	3.1	3.2	3.1	3.2	0.1
MoO_3	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.1
SnO	14.9	14.3	13.9	13.5	15.0	13.5	14.2	0.7
Sb_2O_3	0.2	nd	nd	nd	nd	0.2	0.1	0.1
WO_3	1.5	1.4	1.4	1.1	1.0	1.5	1.3	0.2
Sum	101.0	101.1	101.2	101.4	100.7	100.5	101.0	

Upper Merrivale 2/53

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	3.0	3.8	3.4	3.5	3.2	3.5	3.4	0.3
MgO	4.3	4.6	4.4	4.2	4.1	4.2	4.3	0.2
Al_2O_3	17.7	18.4	18.4	18.2	17.5	17.2	17.9	0.5
SiO_2	47.9	49.2	48.7	47.9	47.8	47.4	48.2	0.7
P_2O_5	0.1	0.3	0.2	0.1	0.2	0.4	0.2	0.1
K_2O	1.5	1.5	1.4	1.4	1.6	1.5	1.5	0.1
CaO	0.8	0.6	0.7	0.9	0.7	0.8	0.8	0.1
TiO_2	3.3	3.0	2.8	2.7	3.1	3.0	3.0	0.2
V_2O_5	nd	0.1	0.1	0.2	0.1	0.1	0.1	0.1
MnO	0.9	0.7	0.6	0.6	0.7	0.7	0.7	0.1
FeO	13.0	11.5	11.7	12.2	13.5	14.0	12.7	1.0
CuO	nd	nd	0.1	nd	nd	nd	nd	-
ZnO	0.1	0.1	0.1	nd	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.2	0.1	0.5	0.3	nd	0.2	0.2
MoO_3	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1
SnO	7.9	7.0	8.3	8.4	7.8	7.9	7.9	0.5
Sb_2O_3	0.1	nd	nd	nd	0.1	nd	0.0	0.1
WO_3	0.5	0.5	0.2	0.5	0.4	0.7	0.5	0.2
Sum	101.5	101.6	101.4	101.4	101.3	101.6	101.5	

Upper Merrivale 2/54

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.5	2.7	2.6	2.4	2.4	2.5	0.1
MgO	3.0	1.8	3.5	3.1	3.4	3.2	3.0	0.6
Al_2O_3	11.6	7.5	12.9	11.7	13.1	12.1	11.5	2.0
SiO_2	33.5	30.5	36.6	33.5	38.3	34.4	34.5	2.7
P_2O_5	0.3	1.2	0.2	0.2	0.5	0.3	0.5	0.4
K_2O	1.0	1.2	1.0	1.0	1.1	1.0	1.1	0.1
CaO	0.8	0.4	0.7	0.8	0.9	0.8	0.7	0.2
TiO_2	8.3	6.2	7.2	7.7	8.1	8.0	7.6	0.8
V_2O_5	0.2	0.1	0.2	nd	0.1	nd	0.1	0.1
MnO	1.0	0.4	0.7	0.9	1.0	0.9	0.8	0.2
FeO	13.0	6.3	11.4	12.4	12.9	12.3	11.4	2.6
CuO	nd	nd	nd	0.1	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	5.4	29.3	6.1	7.8	3.4	9.6	10.3	9.6
MoO_3	0.3	nd	0.2	0.2	0.2	0.2	0.2	0.1
SnO	18.4	13.2	16.7	17.6	14.7	14.4	15.8	2.0
Sb_2O_3	0.5	nd	nd	0.1	0.2	0.3	0.2	0.2
WO_3	1.1	0.3	1.3	1.3	1.1	1.4	1.1	0.3
Sum	100.9	100.9	101.4	101.0	101.4	101.3	101.1	

Upper Merrivale 2/55

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.5	1.3	1.5	1.6	1.2	1.5	0.2
MgO	3.0	2.6	2.9	2.7	3.1	2.8	2.9	0.2
Al_2O_3	11.5	10.8	10.9	10.5	11.0	10.8	10.9	0.3
SiO_2	32.8	30.3	30.9	30.0	31.3	30.6	31.0	1.0
P_2O_5	nd	nd	nd	nd	nd	0.1	0.0	0.0
K_2O	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
CaO	1.0	1.1	0.9	1.0	0.9	1.0	1.0	0.1
TiO_2	6.1	5.9	7.2	7.3	7.1	6.8	6.7	0.6
V_2O_5	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1
MnO	1.2	1.1	1.2	1.1	1.1	1.2	1.2	0.1
FeO	16.3	15.9	16.4	16.1	16.5	16.1	16.2	0.2
CuO	0.1	0.1	nd	0.1	nd	nd	0.1	0.1
ZnO	nd	nd	nd	0.1	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.9	3.2	3.2	3.2	3.2	2.6	3.1	0.3
MoO_3	nd	0.4	0.3	0.4	0.3	0.1	0.3	0.2
SnO	19.9	23.3	21.1	21.8	21.0	23.1	21.7	1.3
Sb_2O_3	0.3	nd	nd	0.1	0.1	0.3	0.1	0.1
WO_3	3.1	3.1	3.4	3.5	2.8	2.8	3.1	0.2
Sum	101.0	100.4	100.9	100.5	101.3	100.6	100.8	

Upper Merrivale 2/56

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.6	2.0	1.7	2.0	2.2	1.6	2.0	0.4
MgO	1.9	1.8	2.2	2.1	2.0	2.1	2.0	0.1
Al_2O_3	11.7	11.3	11.7	12.0	12.0	11.5	11.7	0.3
SiO_2	36.3	35.9	36.9	37.3	37.2	36.4	36.7	0.6
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.2	1.0	1.0	1.1	1.1	1.1	1.1	0.1
CaO	0.4	0.4	0.3	0.2	0.3	0.4	0.3	0.1
TiO_2	12.6	12.9	12.9	12.6	12.6	12.7	12.7	0.1
V_2O_5	0.2	0.1	0.2	nd	0.3	0.2	0.2	0.1
MnO	0.9	1.0	1.0	1.1	1.0	1.0	1.0	0.1
FeO	11.9	11.9	11.5	10.8	11.6	12.1	11.6	0.5
CuO	nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	nd	nd	0.2	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.2	1.0	1.4	1.3	1.3	1.3	1.3	0.1
MoO_3	0.4	0.3	0.4	0.2	0.3	0.5	0.4	0.1
SnO	18.7	19.7	18.7	19.1	17.9	18.7	18.8	0.6
Sb_2O_3	nd	nd	nd	nd	nd	nd	0.0	0.0
WO_3	1.0	1.6	1.2	1.3	1.2	1.5	1.3	0.2
Sum	101.0	101.0	101.3	101.1	101.0	101.1	101.1	

Upper Merrivale 2/57

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	1.8	1.9	2.0	1.8	2.1	1.9	0.1
MgO	3.3	3.2	3.2	3.3	3.4	3.3	3.3	0.1
Al_2O_3	15.9	15.1	15.5	15.5	16.0	15.6	15.6	0.3
SiO_2	39.8	38.4	38.7	39.6	39.9	39.7	39.4	0.6
P_2O_5	0.2	nd	nd	0.4	nd	0.1	0.1	0.2
K_2O	1.0	1.1	1.1	1.1	1.2	1.1	1.1	0.1
CaO	0.9	1.0	1.0	1.1	1.0	0.9	1.0	0.1
TiO_2	7.3	7.0	6.9	7.0	6.8	7.1	7.0	0.2
V_2O_5	0.2	0.1	0.1	nd	0.3	0.1	0.1	0.1
MnO	2.5	2.4	2.3	2.5	2.6	2.4	2.5	0.1
FeO	11.1	10.9	10.9	10.7	10.8	10.8	10.9	0.1
CuO	nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	nd	nd	0.1	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.4	2.5	2.3	2.1	2.6	2.2	2.4	0.2
MoO_3	0.1	0.4	0.2	0.3	0.2	0.2	0.2	0.1
SnO	10.8	12.6	12.5	11.9	11.1	11.4	11.7	0.7
Sb_2O_3	nd	0.4	nd	0.1	nd	0.2	0.1	0.2
WO_3	3.8	4.0	4.4	3.5	3.4	3.8	3.8	0.3
Sum	101.2	101.0	101.1	101.1	101.1	101.0	101.0	

Upper Merrivale 3/24

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	2.2	2.3	1.9	1.8	1.7	2.0	0.2
MgO	3.1	3.1	3.0	3.1	2.7	2.7	3.0	0.2
Al_2O_3	15.6	15.4	15.4	15.4	14.4	14.7	15.2	0.5
SiO_2	40.5	40.5	40.6	40.5	38.5	38.6	39.9	1.0
P_2O_5	nd	nd	nd	nd	nd	0.1	0.0	0.0
K_2O	1.5	1.6	1.6	1.6	1.7	1.6	1.6	0.1
CaO	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.1
TiO_2	5.3	5.3	5.2	5.4	5.7	5.7	5.4	0.2
V_2O_5	nd	0.1	0.1	nd	0.1	0.3	0.1	0.1
MnO	1.0	0.9	1.0	0.9	1.1	1.0	1.0	0.1
FeO	10.6	10.6	10.4	10.5	11.8	11.2	10.9	0.5
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.1	nd	0.2	0.1	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.7	1.7	1.7	1.3	1.5	1.3	1.5	0.2
MoO_3	0.3	0.2	nd	0.1	0.2	0.3	0.2	0.1
SnO	15.3	15.9	15.3	15.6	16.3	16.2	15.8	0.4
Sb_2O_3	nd	nd	nd	nd	nd	0.1	0.0	0.0
WO_3	3.5	2.9	3.8	4.0	4.8	4.1	3.9	0.6
Sum	101.1	101.0	101.2	101.1	101.3	100.4	101.0	

Upper Merrivale 3/27

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.0	0.9	1.2	1.2	0.8	1.0	0.2
MgO	1.6	1.6	1.2	1.4	1.6	1.5	1.5	0.2
Al_2O_3	10.2	10.2	10.7	10.2	10.1	9.9	10.2	0.3
SiO_2	29.2	29.2	28.0	28.3	28.7	28.2	28.6	0.5
P_2O_5	0.1	0.1	0.1	0.2	nd	nd	0.1	0.1
K_2O	1.3	1.3	1.3	1.3	1.3	1.3	1.3	0.0
CaO	1.0	1.0	0.8	0.8	0.8	1.0	0.9	0.1
TiO_2	3.5	3.5	4.9	4.5	4.2	4.2	4.1	0.6
V_2O_5	0.1	0.1	0.1	nd	0.2	0.1	0.1	0.1
MnO	2.7	2.7	2.5	2.5	2.4	2.7	2.6	0.1
FeO	35.9	34.8	37.0	36.7	38.8	37.3	36.8	1.3
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	0.3	0.3	nd	nd	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	0.6	0.7	0.6	0.9	0.6	0.7	0.1
MoO_3	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.1
SnO	10.2	12.2	9.4	9.9	9.0	10.3	10.2	1.1
Sb_2O_3	nd	nd	nd	nd	nd	0.1	0.0	0.0
WO_3	2.4	2.8	2.4	2.4	1.9	2.0	2.3	0.2
Sum	100.2	101.5	100.3	100.2	101.3	100.4	100.7	

Metherel 2/48

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.8	0.9	0.9	1.1	0.8	1.2	1.0	0.2
MgO	1.0	1.1	1.3	1.2	1.4	1.1	1.2	0.1
Al_2O_3	10.2	9.7	9.9	10.0	11.5	10.0	10.2	0.6
SiO_2	20.3	20.1	20.5	20.1	23.5	20.1	20.8	1.3
P_2O_5	nd	nd	nd	nd	nd	nd	0.0	0.0
K_2O	1.6	1.4	1.4	1.4	1.8	1.5	1.5	0.2
CaO	1.5	1.0	1.3	1.3	1.6	1.4	1.4	0.2
TiO_2	2.2	1.9	1.9	2.2	2.6	2.2	2.2	0.3
V_2O_5	0.1	nd	nd	nd	nd	0.1	0.0	0.1
MnO	2.3	2.1	2.2	2.3	2.6	2.3	2.3	0.2
FeO	10.3	9.1	9.7	10.0	10.9	9.9	10.0	0.6
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	0.1	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.1	0.1	0.1	0.2	0.3	0.2	0.1
MoO_3	0.4	0.2	nd	nd	0.4	0.3	0.2	0.2
SnO	51.3	54.0	53.8	53.7	63.2	52.5	54.8	4.3
Sb_2O_3	nd	nd	nd	nd	nd	nd	0.0	0.0
WO_3	0.4	0.5	nd	0.1	0.6	0.4	0.3	0.2
Sum	102.8	102.1	103.0	103.5	121.2	103.3	106.0	

Metherel 2/49

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.9	1.0	1.1	1.3	1.4	1.2	1.2	0.2
MgO	1.1	0.8	1.0	1.0	0.9	0.9	1.0	0.1
Al_2O_3	6.4	6.5	6.7	6.9	7.1	7.1	6.8	0.3
SiO_2	19.2	18.8	18.9	20.2	20.2	20.3	19.6	0.7
P_2O_5	nd	0.1	nd	nd	nd	nd	0.0	0.0
K_2O	0.8	0.8	0.7	0.9	1.0	0.9	0.9	0.1
CaO	0.7	0.4	0.4	0.3	0.1	0.2	0.4	0.2
TiO_2	1.0	0.9	1.1	1.0	1.0	1.2	1.0	0.1
V_2O_5	nd	nd	nd	nd	nd	nd	nd	-
MnO	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.1
FeO	11.9	10.2	10.7	10.4	10.7	10.6	10.8	0.6
CuO	nd	0.2	nd	nd	nd	nd	0.0	0.1
ZnO	nd	nd	0.2	nd	0.2	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	0.2	0.1	nd	0.1	0.1	0.1
MoO_3	0.1	nd	0.3	0.2	nd	0.1	0.1	0.1
SnO	59.7	62.3	61.1	59.2	58.8	59.9	60.2	1.3
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	-
WO_3	nd	nd	nd	nd	0.1	nd	0.0	0.0
Sum	102.3	102.4	102.9	101.9	102	102.9	102.4	

Nosworthy 3/16

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	1.9	1.6	1.6	1.7	1.4	1.7	0.2
MgO	2.9	2.9	3.0	2.9	2.8	2.8	2.9	0.1
Al_2O_3	12.2	11.3	11.7	11.6	12.2	11.4	11.7	0.4
SiO_2	33.0	31.2	30.3	31.2	32.4	30.5	31.4	1.1
P_2O_5	0.3	0.5	0.3	0.2	0.4	0.4	0.4	0.1
K_2O	1.4	1.4	1.4	1.4	1.6	1.4	1.4	0.1
CaO	1.0	1.1	1.0	0.9	1.0	0.9	1.0	0.1
TiO_2	10.4	10.7	11.4	12.4	9.7	10.5	10.9	0.9
V_2O_5	0.2	0.2	0.4	0.5	0.3	0.2	0.3	0.1
MnO	1.4	1.4	1.2	1.3	1.3	1.3	1.3	0.1
FeO	20.0	20.0	19.1	20.3	19.9	19.1	19.7	0.5
CuO	0.2	nd	nd	nd	nd	nd	0.0	0.1
ZnO	nd	nd	nd	nd	nd	0.1	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.1	2.0	2.2	2.1	1.9	2.1	2.1	0.1
MoO_3	0.1	nd	nd	nd	0.1	0.1	0.1	0.1
SnO	16.0	15.4	15.5	17.1	18.0	17.1	16.5	1.0
Sb_2O_3	0.1	0.4	0.1	nd	0.4	0.2	0.2	0.2
WO_3	1.2	1.3	0.8	1.4	0.9	1.6	1.2	0.3
Sum	104.6	101.7	100.0	104.9	104.6	101.1	102.8	

Nosworthy 3/17

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.3	1.5	1.2	1.4	1.0	1.2	0.2
MgO	2.3	2.1	2.1	2.4	2.3	2.3	2.3	0.1
Al_2O_3	10.1	9.6	10.1	9.7	9.9	10.2	9.9	0.2
SiO_2	27.7	26.5	27.1	26.3	26.6	27.8	27.0	0.6
P_2O_5	0.3	0.1	nd	0.1	0.5	0.1	0.2	0.2
K_2O	1.5	1.6	1.5	1.5	1.5	1.4	1.5	0.1
CaO	1.0	1.0	1.1	1.0	1.0	1.1	1.0	0.1
TiO_2	11.5	12.5	12.1	11.2	12.0	11.2	11.8	0.5
V_2O_5	0.3	0.4	0.3	0.2	0.3	0.2	0.3	0.1
MnO	1.7	1.6	1.6	1.4	1.4	1.6	1.6	0.1
FeO	23.1	23.7	23.3	23.6	23.2	22.9	23.3	0.3
CuO	0.1	nd	nd	nd	0.1	nd	0.0	0.1
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.6	1.7	2.0	1.7	1.6	2.0	1.8	0.2
MoO_3	nd	nd	nd	nd	nd	nd	nd	-
SnO	17.8	17.8	16.7	18.3	16.6	17.3	17.4	0.7
Sb_2O_3	nd	0.1	nd	0.6	0.2	0.4	0.2	0.2
WO_3	1.2	1.1	1.4	1.6	2.0	1.2	1.4	0.3
Sum	101.2	101.1	100.8	100.8	100.6	100.7	100.9	

Outer Down 4/18

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.0	2.1	2.0	4.7	2.0	2.1	2.5	1.1
MgO	1.3	1.3	1.2	0.4	1.0	1.2	1.1	0.3
Al_2O_3	12.5	13.3	12.5	20.2	12.9	12.9	14.1	3.0
SiO_2	33.6	36.5	35.8	63.7	35.7	35.8	40.2	11.6
P_2O_5	0.4	0.1	nd	nd	0.2	0.1	0.1	0.2
K_2O	2.8	3.1	3.1	9.9	3.0	3.0	4.2	2.8
CaO	1.4	1.6	1.7	0.6	1.6	1.7	1.4	0.4
TiO_2	11.7	10.8	12.2	0.3	11.0	11.7	9.6	4.6
V_2O_5	0.2	0.1	0.2	nd	0.2	0.1	0.1	0.1
MnO	0.6	0.6	0.6	nd	0.5	0.7	0.5	0.3
FeO	18.7	17.8	18.2	13.4	18.3	19.0	17.6	2.1
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	0.1	0.1	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.5	0.8	nd	0.6	0.6	0.5	0.3
MoO_3	nd	nd	nd	0.1	nd	nd	0.0	0.0
SnO	15.0	12.2	11.7	1.6	12.2	11.9	10.8	4.7
Sb_2O_3	nd	0.3	nd	nd	0.2	nd	0.1	0.1
WO_3	0.6	0.2	0.4	nd	0.9	0.3	0.4	0.3
Sum	101.1	100.5	100.5	114.9	100.4	101.2	103.1	

Retallack 4/01

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	1.8	2.1	1.5	1.8	1.8	1.8	0.2
MgO	1.7	1.7	1.8	1.7	1.6	1.8	1.7	0.1
Al_2O_3	14.7	14.7	14.5	13.8	14.4	14.6	14.5	0.3
SiO_2	36.7	37.1	36.8	35.3	35.3	36.6	36.3	0.8
P_2O_5	0.1	0.5	0.1	0.1	0.2	0.4	0.2	0.2
K_2O	3.9	3.9	3.9	3.7	3.5	3.9	3.8	0.2
CaO	4.1	4.1	4.0	3.7	3.7	3.9	3.9	0.2
TiO_2	1.0	1.1	1.0	0.8	0.9	1.1	1.0	0.1
V_2O_5	nd	nd	0.1	0.1	nd	nd	0.0	0.1
MnO	0.3	0.3	0.5	0.4	0.3	0.4	0.4	0.1
FeO	12.0	12.1	12.6	12.3	11.8	12.5	12.2	0.3
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	0.3	0.1	0.3	nd	nd	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	nd	0.4	0.3	0.3	0.1	0.2	0.2
MoO_3	0.2	0.3	0.1	0.1	0.4	nd	0.2	0.1
SnO	21.9	21.1	22.1	25.7	21.1	22.5	22.4	1.7
Sb_2O_3	0.2	0.4	0.2	0.4	0.1	0.4	0.3	0.1
WO_3	1.8	2.1	1.0	1.3	1.7	1.4	1.6	0.4
Sum	101.1	101.3	101.6	101.2	97.1	101.4	100.6	

Retallack 4/02

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.5	1.6	1.4	1.7	1.6	1.6	1.6	0.1
MgO	1.4	1.4	1.5	1.6	1.5	1.2	1.4	0.1
Al_2O_3	13.3	13.0	12.9	13.3	13.7	13.0	13.2	0.3
SiO_2	42.5	41.1	40.7	41.6	42.0	40.8	41.5	0.7
P_2O_5	nd	0.1	0.2	0.2	0.2	nd	0.1	0.1
K_2O	3.3	3.2	3.2	3.2	3.2	3.3	3.2	0.1
CaO	4.2	4.3	4.1	4.4	4.3	4.3	4.3	0.1
TiO_2	1.0	1.0	0.9	1.0	1.0	1.1	1.0	0.1
V_2O_5	0.1	0.1	0.1	nd	0.1	nd	0.1	0.1
MnO	0.4	0.5	0.5	0.6	0.6	0.5	0.5	0.1
FeO	12.3	12.7	12.4	12.5	13.0	12.0	12.5	0.3
CuO	0.2	nd	nd	nd	nd	nd	0.0	0.1
ZnO	0.1	nd	0.2	0.1	0.4	0.2	0.2	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.1	nd	0.1	nd	0.3	0.2	0.2
MoO_3	0.4	0.1	0.1	0.2	0.3	0.3	0.2	0.1
SnO	16.9	16.7	19.6	17.2	16.1	18.4	17.5	1.3
Sb_2O_3	0.4	0.1	nd	0.1	nd	0.5	0.2	0.2
WO_3	1.4	1.6	1.2	1.2	1.5	1.7	1.4	0.2
Sum	99.8	97.6	99.0	99.0	99.5	99.2	99.0	

Retallack 4/03

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.3	1.6	1.5	1.6	1.5	1.5	0.1
MgO	1.2	1.2	1.3	1.3	1.3	1.2	1.3	0.1
Al_2O_3	12.3	12.3	11.8	12.0	13.7	11.2	12.2	0.8
SiO_2	33.9	36.2	33.0	34.2	39.7	32.4	34.9	2.7
P_2O_5	0.3	0.3	nd	0.3	0.3	0.1	0.2	0.1
K_2O	3.4	3.5	3.3	3.5	3.9	3.3	3.5	0.2
CaO	3.4	3.5	3.4	3.5	4.2	3.3	3.6	0.3
TiO_2	0.6	0.5	0.5	0.5	0.5	0.3	0.5	0.1
V_2O_5	nd	nd	nd	0.1	nd	0.2	0.1	0.1
MnO	0.3	0.5	0.2	0.4	0.5	0.4	0.4	0.1
FeO	8.3	7.6	7.6	7.8	8.1	7.5	7.8	0.3
CuO	nd	nd	nd	0.1	0.1	nd	0.0	0.1
ZnO	nd	0.2	nd	nd	nd	0.4	0.1	0.2
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	0.2	0.5	0.1	0.1	0.3	0.2	0.2
MoO_3	0.2	nd	0.3	0.1	0.2	0.2	0.2	0.1
SnO	34.9	29.5	33.3	33.6	27.1	35.0	32.2	3.2
Sb_2O_3	0.1	nd	0.2	0.4	0.1	nd	0.1	0.2
WO_3	0.6	1.6	0.6	0.2	0.2	1.5	0.8	0.6
Sum	101.1	98.4	97.6	99.6	101.6	98.8	99.5	

Riddon 2/38

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	1.9	2.5	1.3	1.4	1.6	1.8	0.4
MgO	2.9	2.9	2.7	3.0	2.9	2.9	2.9	0.1
Al_2O_3	12.8	13.5	13.3	13.1	13.3	13.2	13.2	0.2
SiO_2	40.8	42.1	41.8	41.5	41.4	41.1	41.5	0.5
P_2O_5	0.2	nd	0.1	0.3	0.1	0.4	0.2	0.1
K_2O	1.7	1.6	1.6	1.6	1.7	1.6	1.6	0.1
CaO	0.6	0.6	0.7	0.8	0.6	0.7	0.7	0.1
TiO_2	4.9	5.0	4.9	5.1	5.1	5.2	5.0	0.1
V_2O_5	0.1	0.2	0.1	nd	0.1	0.2	0.1	0.1
MnO	0.5	0.6	0.4	0.4	0.4	0.6	0.5	0.1
FeO	20.6	21.2	20.3	21.1	21.1	21.6	21.0	0.5
CuO	0.1	nd	nd	nd	nd	nd	0.0	0.0
ZnO	0.3	nd	nd	nd	nd	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	0.4	0.3	nd	0.4	nd	0.2	0.2
MoO_3	0.3	0.2	0.2	nd	0.3	0.1	0.2	0.1
SnO	12.0	10.8	11.6	12.7	11.4	11.3	11.6	0.7
Sb_2O_3	0.1	0.1	nd	0.3	0.1	nd	0.1	0.1
WO_3	1.1	0.2	0.4	nd	0.6	0.2	0.4	0.4
Sum	100.8	101.3	100.9	101.2	100.9	100.7	101.0	

Riddon 2/39

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.3	1.3	1.7	1.3	1.6	1.5	1.5	0.2
MgO	2.8	2.7	2.8	3.0	3.0	2.7	2.8	0.1
Al_2O_3	13.8	13.6	13.7	13.5	13.4	13.7	13.6	0.1
SiO_2	41.9	41.7	41.5	41.9	41.1	41.9	41.7	0.3
P_2O_5	0.3	0.2	0.2	0.2	0.1	nd	0.2	0.1
K_2O	1.8	1.7	1.8	1.6	1.8	1.8	1.8	0.1
CaO	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.0
TiO_2	5.4	5.7	5.6	5.9	5.4	5.5	5.6	0.2
V_2O_5	0.2	nd	0.2	0.1	0.1	0.1	0.1	0.1
MnO	0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.1
FeO	20.0	19.3	19.3	20.9	19.8	19.4	19.8	0.6
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.1	0.1	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.4	0.3	0.2	0.5	0.7	0.4	0.2
MoO_3	nd	nd	nd	nd	0.2	0.1	0.1	0.1
SnO	11.7	12.3	12.2	11.0	12.9	11.5	11.9	0.7
Sb_2O_3	0.1	0.4	0.1	0.1	0.1	nd	0.1	0.1
WO_3	0.2	nd	nd	0.2	nd	0.2	0.1	0.1
Sum	101.0	100.7	100.8	101.2	101.4	100.5	100.9	

South Hill I 2/42

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	2.0	1.7	1.8	1.8	1.8	1.9	0.2
MgO	2.1	2.0	2.0	2.0	2.0	2.0	2.0	0.0
Al_2O_3	11.9	11.9	12.0	11.5	11.8	11.9	11.8	0.2
SiO_2	36.3	36.0	36.2	34.9	36.0	35.9	35.9	0.5
P_2O_5	0.2	0.3	0.3	0.4	0.3	0.4	0.3	0.1
K_2O	2.7	2.8	2.6	2.7	2.8	2.8	2.7	0.1
CaO	1.9	1.7	1.8	1.9	1.8	1.8	1.8	0.1
TiO_2	12.5	12.8	12.9	13.6	13.0	13.3	13.0	0.4
V_2O_5	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.1
MnO	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.0
FeO	20.3	20.2	20.9	21.2	20.3	20.4	20.6	0.4
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.7	0.8	0.5	0.6	0.7	0.5	0.6	0.1
MoO_3	0.1	0.3	0.2	0.1	0.2	0.1	0.2	0.1
SnO	8.0	8.0	8.4	8.1	8.3	8.0	8.1	0.2
Sb_2O_3	0.1	nd	0.2	0.2	0.2	0.2	0.2	0.1
WO_3	1.0	0.9	0.6	0.7	0.5	0.7	0.7	0.2
Sum	101.0	100.8	101.3	100.8	100.8	100.9	100.9	

South Hill I 2/43

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.8	1.9	1.8	1.9	1.9	2.0	0.4
MgO	3.1	2.1	3.0	3.1	3.0	3.0	2.9	0.4
Al_2O_3	14.3	15.7	14.6	15.0	14.6	14.3	14.8	0.5
SiO_2	40.0	53.3	40.7	40.5	40.3	40.4	42.5	5.3
P_2O_5	0.3	nd	0.3	0.3	0.2	0.2	0.2	0.1
K_2O	1.9	3.9	2.0	2.0	2.0	2.0	2.3	0.8
CaO	1.1	0.9	1.2	1.1	1.2	1.1	1.1	0.1
TiO_2	9.5	5.9	9.8	9.1	9.4	9.6	8.9	1.5
V_2O_5	0.3	0.2	0.1	0.4	0.3	0.2	0.3	0.1
MnO	1.1	0.7	1.1	1.2	1.1	1.2	1.1	0.2
FeO	17.2	10.0	17.4	17.3	17.2	17.5	16.1	3.0
CuO	nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	0.1	nd	nd	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.0	0.6	0.8	0.7	1.1	1.1	0.9	0.2
MoO_3	0.1	0.1	nd	nd	0.2	0.1	0.1	0.1
SnO	7.7	4.1	7.0	6.9	6.8	7.2	6.6	1.3
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	-
WO_3	1.5	0.7	1.1	1.4	1.5	0.9	1.2	0.3
Sum	101.1	101.1	101.0	100.8	100.8	100.7	100.9	

South Hill II 2/17

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.7	1.6	1.5	1.6	1.7	1.6	0.1
MgO	2.4	2.2	2.1	2.2	2.1	2.1	2.2	0.1
Al_2O_3	12.5	12.7	12.9	12.5	12.8	12.5	12.7	0.2
SiO_2	35.6	35.3	35.7	35.4	35.4	35.1	35.4	0.2
P_2O_5	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.0
K_2O	1.9	1.7	1.9	1.8	1.9	1.9	1.9	0.1
CaO	0.8	0.8	0.8	0.7	0.7	0.8	0.8	0.1
TiO_2	11.1	10.9	11.0	11.4	11.1	11.0	11.1	0.2
V_2O_5	0.2	0.2	0.2	0.1	0.1	0.3	0.2	0.1
MnO	0.8	0.7	0.8	0.7	0.7	0.7	0.7	0.1
FeO	20.2	20.7	21.2	21.1	20.9	20.6	20.8	0.4
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	0.1	nd	nd	nd	0.1	0.2	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.5	0.3	0.1	0.2	0.4	0.3	0.1
MoO_3	nd	nd	nd	nd	0.1	0.1	0.0	0.1
SnO	12.4	11.9	12.0	12.3	12.2	12.2	12.2	0.2
Sb_2O_3	0.1	0.2	nd	0.1	nd	0.1	0.1	0.1
WO_3	1.2	0.8	0.6	0.6	0.6	1.0	0.8	0.2
Sum	101.4	100.5	101.3	100.7	100.7	100.8	100.9	

Stannon Brook 2/02

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.4	1.4	1.7	1.7	1.6	1.6	1.6	0.1
MgO	2.5	2.5	2.6	2.7	2.5	2.5	2.6	0.1
Al_2O_3	12.7	12.6	12.9	13.0	12.9	12.8	12.8	0.1
SiO_2	41.1	40.5	40.9	40.7	41.3	40.7	40.9	0.3
P_2O_5	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.1
K_2O	2.4	2.2	2.3	2.3	2.3	2.2	2.3	0.1
CaO	1.1	1.1	1.0	1.1	1.2	1.1	1.1	0.1
TiO_2	10.5	10.5	10.4	10.7	11.1	10.8	10.7	0.3
V_2O_5	0.3	0.3	0.3	0.3	0.1	0.3	0.3	0.1
MnO	0.8	0.9	0.9	0.9	0.8	0.9	0.9	0.1
FeO	20.3	20.8	19.6	20.5	19.5	20.2	20.2	0.5
CuO	nd	nd	0.2	nd	0.1	0.1	0.1	0.1
ZnO	nd	0.1	0.1	nd	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.1	0.3	0.2	0.1	nd	0.1	0.1	0.1
MoO_3	0.2	0.1	0.2	nd	0.1	nd	0.1	0.1
SnO	7.0	7.4	6.9	6.8	6.5	6.6	6.9	0.3
Sb_2O_3	0.2	nd	0.1	0.1	0.2	0.1	0.1	0.1
WO_3	0.1	nd	0.2	nd	0.2	0.2	0.1	0.1
Sum	101.0	100.9	100.7	101.1	100.6	100.6	100.8	

Stannon Brook 2/03

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.9	1.4	1.5	1.5	1.1	1.5	0.3
MgO	3.5	3.5	3.6	3.6	3.6	3.5	3.6	0.1
Al_2O_3	12.8	12.7	12.7	12.3	12.8	12.5	12.6	0.2
SiO_2	43.1	43.2	43.0	42.1	42.8	42.2	42.7	0.5
P_2O_5	0.3	0.1	nd	0.2	0.1	nd	0.1	0.1
K_2O	1.7	1.9	1.7	1.8	1.7	1.7	1.8	0.1
CaO	0.8	0.9	0.8	0.9	0.8	0.8	0.8	0.1
TiO_2	4.5	4.6	4.4	4.3	4.5	4.4	4.5	0.1
V_2O_5	nd	0.1	nd	0.1	0.1	0.2	0.1	0.1
MnO	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.0
FeO	23.4	22.5	21.9	22.8	22.9	23.3	22.8	0.6
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	nd	nd	0.3	nd	nd	0.1	0.1	0.1
MoO_3	nd	0.2	0.1	nd	0.1	nd	0.1	0.1
SnO	9.4	8.8	9.9	10.4	10.0	10.7	9.9	0.7
Sb_2O_3	nd	0.3	nd	0.3	nd	nd	0.1	0.2
WO_3	nd	nd	0.7	0.1	nd	0.1	0.1	0.2
Sum	101.5	101.1	100.9	100.9	101.3	101.1	101.1	

Stannon Brook 2/04

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.7	2.4	2.1	2.1	2.0	2.2	2.3	0.3
MgO	3.0	3.1	3.3	3.4	3.4	3.0	3.2	0.2
Al_2O_3	14.3	14.5	14.4	14.5	14.3	14.6	14.4	0.1
SiO_2	43.7	44.7	44.5	44.8	43.6	45.3	44.4	0.7
P_2O_5	nd	0.1	0.1	0.4	nd	0.1	0.1	0.1
K_2O	2.0	2.1	2.1	2.0	2.0	2.1	2.1	0.1
CaO	0.8	0.9	1.0	0.9	0.9	0.9	0.9	0.1
TiO_2	8.6	9.4	9.3	9.2	9.3	9.2	9.2	0.3
V_2O_5	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.1
MnO	0.7	0.6	0.8	0.7	0.8	0.7	0.7	0.1
FeO	15.7	15.8	15.8	16.2	16.2	15.4	15.9	0.3
CuO	nd	0.2	nd	nd	nd	nd	0.0	0.1
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.1	0.2	nd	0.4	nd	0.2	0.2
MoO_3	0.1	nd	0.2	0.1	nd	nd	0.1	0.1
SnO	8.4	7.3	7.1	7.5	8.1	7.2	7.6	0.5
Sb_2O_3	nd	nd	nd	nd	nd	nd	nd	-
WO_3	0.5	nd	0.4	nd	0.3	0.1	0.2	0.2
Sum	100.9	101.3	101.4	102.0	101.5	101.0	101.3	

Stannon Brook 4/25

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.1	2.3	2.2	2.5	2.1	2.2	2.2	0.2
MgO	3.1	3.1	3.4	3.3	3.6	3.3	3.3	0.2
Al_2O_3	14.6	14.7	14.9	15.3	15.8	14.9	15.0	0.4
SiO_2	46.9	48.1	47.7	49.4	50.2	48.4	48.5	1.2
P_2O_5	0.1	nd	0.1	0.2	0.1	0.3	0.1	0.1
K_2O	1.1	1.1	1.1	1.1	1.2	1.2	1.1	0.1
CaO	0.9	0.8	0.8	0.9	0.9	0.9	0.9	0.1
TiO_2	2.1	1.9	2.0	2.1	2.1	1.9	2.0	0.1
V_2O_5	0.1	0.2	0.1	nd	0.1	0.1	0.1	0.1
MnO	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.1
FeO	14.7	14.2	14.3	15.3	15.3	14.4	14.7	0.5
CuO	nd	0.2	nd	nd	nd	nd	0.0	0.1
ZnO	nd	0.1	0.3	nd	nd	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.4	0.3	0.2	0.5	0.2	0.3	0.1
MoO_3	0.1	0.2	0.2	nd	0.3	0.1	0.2	0.1
SnO	10.3	8.6	9.6	9.8	8.6	8.5	9.2	0.8
Sb_2O_3	0.6	nd	nd	nd	nd	0.1	0.1	0.2
WO_3	nd	nd	0.7	0.1	0.2	0.1	0.2	0.3
Sum	97.4	96.4	98.3	100.7	101.6	97.1	98.6	

Taw River 2/15

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	1.2	1.4	1.5	1.6	1.4	1.5	0.2
MgO	2.8	2.8	2.7	2.7	2.8	3.0	2.8	0.1
Al_2O_3	9.9	9.4	9.4	9.5	9.4	9.6	9.5	0.2
SiO_2	24.5	23.1	23.2	23.5	23.8	23.7	23.6	0.5
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	0.7	0.7	0.8	0.8	0.6	0.8	0.7	0.1
CaO	0.6	0.6	0.7	0.6	0.7	0.6	0.6	0.1
TiO_2	9.1	9.5	10.4	8.4	9.0	8.9	9.2	0.7
V_2O_5	nd	0.2	0.2	0.2	nd	0.1	0.1	0.1
MnO	1.2	1.3	1.2	1.2	1.1	1.1	1.2	0.1
FeO	11.0	11.6	11.7	10.8	11.1	11.0	11.2	0.4
CuO	0.1	nd	0.1	nd	nd	nd	0.0	0.1
ZnO	nd	nd	nd	nd	0.1	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	3.2	3.6	3.6	3.5	2.9	3.0	3.3	0.3
MoO_3	0.3	0.6	0.5	0.3	0.4	0.4	0.4	0.1
SnO	31.1	31.2	30.2	31.9	30.1	31.9	31.1	0.8
Sb_2O_3	0.1	0.2	0.3	0.8	nd	0.4	0.3	0.3
WO_3	6.4	5.9	6.8	7.1	6.8	5.9	6.5	0.5
Sum	102.6	101.9	103.2	102.8	100.4	101.8	102.1	

Taw River 2/40

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.5	1.4	1.4	1.6	1.3	1.7	1.5	0.1
MgO	2.9	2.9	2.8	3.1	3.1	3.2	3.0	0.2
Al_2O_3	9.5	9.4	9.4	10.1	9.6	10.2	9.7	0.4
SiO_2	29.2	28.9	29.2	30.4	29.1	30.5	29.6	0.7
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.1	1.0	1.1	1.1	1.0	1.1	1.1	0.1
CaO	0.7	0.7	0.6	0.9	0.9	0.7	0.8	0.1
TiO_2	8.7	8.4	8.6	8.4	8.5	8.0	8.4	0.2
V_2O_5	0.1	0.1	0.3	0.2	0.3	nd	0.2	0.1
MnO	1.6	1.6	1.5	1.5	1.5	1.6	1.6	0.1
FeO	12.2	12.0	12.0	12.2	11.9	12.1	12.1	0.1
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	0.2	nd	nd	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	4.6	4.4	4.6	4.3	4.6	4.5	4.5	0.1
MoO_3	0.5	0.5	0.8	0.8	1.0	0.6	0.7	0.2
SnO	19.2	20.3	19.9	18.5	19.7	18.5	19.4	0.7
Sb_2O_3	0.6	nd	nd	0.4	nd	0.1	0.2	0.3
WO_3	9.4	10.0	10.1	8.5	9.4	9.3	9.5	0.5
Sum	101.8	101.8	102.4	102.0	101.9	102.1	102.1	

Taw River 2/41

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	2.0	2.2	2.2	2.1	1.9	2.0	0.2
MgO	5.0	4.9	5.1	4.9	5.1	4.8	5.0	0.1
Al_2O_3	14.2	13.9	14.7	14.6	14.7	14.2	14.4	0.3
SiO_2	39.1	39.2	41.1	40.5	41.0	40.0	40.2	0.9
P_2O_5	0.2	0.3	0.2	0.4	0.1	0.2	0.2	0.1
K_2O	1.5	1.4	1.6	1.6	1.4	1.4	1.5	0.1
CaO	1.0	1.1	1.2	1.1	1.1	1.1	1.1	0.1
TiO_2	8.9	8.8	9.2	9.3	9.6	9.2	9.2	0.3
V_2O_5	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.1
MnO	1.3	1.3	1.2	1.4	1.3	1.2	1.3	0.1
FeO	13.4	12.7	12.6	12.9	12.9	12.7	12.9	0.3
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	2.9	2.4	2.5	2.6	2.6	2.7	2.6	0.2
MoO_3	0.1	0.1	0.1	nd	nd	nd	0.1	0.1
SnO	9.0	10.1	7.6	7.7	7.9	8.8	8.5	1.0
Sb_2O_3	0.2	nd	nd	nd	nd	nd	0.0	0.1
WO_3	2.9	2.8	1.4	1.9	2.0	2.5	2.2	0.5
Sum	101.6	101.2	101.0	101.3	102.0	100.8	101.3	

Teignhead Farm 2/14

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.6	2.1	2.2	2.3	3.1	1.9	2.2	0.5
MgO	2.5	2.6	2.7	2.9	2.8	2.5	2.7	0.2
Al_2O_3	11.0	12.1	11.9	12.5	13.2	11.8	12.1	0.7
SiO_2	33.4	35.7	35.0	36.3	37.9	35.5	35.6	1.5
P_2O_5	0.4	0.2	0.3	0.4	0.2	0.2	0.3	0.1
K_2O	2.2	2.3	2.1	2.2	2.1	2.2	2.2	0.1
CaO	1.7	1.4	1.4	1.5	1.3	1.4	1.5	0.1
TiO_2	14.2	12.9	13.8	13.0	12.0	13.7	13.3	0.8
V_2O_5	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.1
MnO	1.0	1.1	0.9	0.9	0.8	0.9	0.9	0.1
FeO	20.6	18.1	19.1	18.0	16.6	19.2	18.6	1.4
CuO	nd	0.2	nd	nd	nd	nd	0.0	0.1
ZnO	0.1	nd	nd	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.3	0.6	nd	0.2	0.4	0.3	0.3	0.2
MoO_3	0.2	0.1	nd	nd	nd	nd	0.1	0.1
SnO	10.5	10.3	10.3	10.5	9.7	10.4	10.3	0.3
Sb_2O_3	0.2	nd	0.2	0.2	nd	nd	0.1	0.1
WO_3	0.8	0.8	0.7	0.3	0.4	0.6	0.6	0.2
Sum	100.8	100.8	100.8	101.3	100.7	100.8	100.8	

Thornworthy 2/45

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.1	1.9	2.0	2.0	2.0	2.0	0.1
MgO	1.8	1.7	1.8	1.6	1.5	1.6	1.7	0.1
Al_2O_3	12.1	12.2	12.6	12.1	12.3	11.9	12.2	0.2
SiO_2	35.0	33.6	35.1	33.7	34.4	33.3	34.2	0.8
P_2O_5	0.4	0.2	0.2	0.3	0.3	0.5	0.3	0.1
K_2O	3.7	3.8	3.7	3.8	3.8	3.5	3.7	0.1
CaO	3.5	3.1	3.6	3.3	3.3	3.6	3.4	0.2
TiO_2	12.2	12.3	11.9	12.5	12.0	12.6	12.3	0.3
V_2O_5	0.2	0.2	0.2	0.2	0.2	nd	0.2	0.1
MnO	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
FeO	23.0	23.9	22.6	23.3	23.8	23.7	23.4	0.5
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	0.1	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.1	0.3	0.2	0.3	nd	nd	0.2	0.1
MoO_3	nd	0.1	nd	nd	nd	nd	0.0	0.0
SnO	5.9	5.4	5.9	5.6	5.5	6.4	5.8	0.4
Sb_2O_3	nd	nd	nd	0.1	0.1	0.1	0.1	0.1
WO_3	0.3	0.6	0.1	1.0	0.3	0.3	0.4	0.3
Sum	101.1	100.5	100.8	100.8	100.5	100.6	100.7	

Thornworthy 2/46

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.5	0.7	0.8	0.9	1.0	0.7	0.8	0.2
MgO	0.6	0.5	0.4	0.6	0.6	0.6	0.6	0.1
Al_2O_3	7.1	7.7	7.1	6.9	6.7	6.8	7.1	0.4
SiO_2	25.9	30.0	27.3	24.9	24.7	25.0	26.3	2.1
P_2O_5	0.1	nd	nd	nd	nd	0.1	0.0	0.1
K_2O	1.5	1.8	1.4	1.5	1.5	1.5	1.5	0.1
CaO	0.8	0.9	0.8	0.6	0.8	0.7	0.8	0.1
TiO_2	12.5	9.5	9.7	11.8	11.8	10.9	11.0	1.2
V_2O_5	0.1	0.2	nd	0.3	0.2	0.1	0.2	0.1
MnO	1.1	1.0	1.0	0.9	1.0	0.9	1.0	0.1
FeO	36.1	33.5	31.8	34.6	35.1	34.0	34.2	1.5
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	0.1	nd	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.9	0.5	0.6	0.5	0.4	0.6	0.2
MoO_3	nd	0.1	nd	nd	nd	nd	0.0	0.0
SnO	18.2	22.2	18.9	16.3	16.6	18.3	18.4	2.1
Sb_2O_3	0.4	nd	nd	nd	nd	nd	0.1	0.2
WO_3	0.9	nd	0.9	0.8	0.4	0.5	0.6	0.3
Sum	106.2	109.0	100.7	100.7	100.9	100.5	103.1	

Trereife (Stable Hobba) 3/35

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.5	0.6	0.3	0.7	0.7	0.4	0.5	0.2
MgO	0.4	0.2	0.3	nd	0.3	nd	0.2	0.2
Al_2O_3	11.8	10.5	10.3	9.3	11.4	10.7	10.7	0.9
SiO_2	28.2	28.8	29.7	28.3	28.5	25.3	28.1	1.5
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.2	1.2	1.3	1.3	1.3	0.9	1.2	0.2
CaO	1.8	1.8	1.7	1.9	1.9	1.3	1.7	0.2
TiO_2	2.1	1.4	1.1	1.5	1.1	1.3	1.4	0.4
V_2O_5	nd	nd	0.1	nd	nd	nd	0.0	0.0
MnO	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.0
FeO	29.3	26.5	28.1	23.1	27.6	27.3	27.0	2.1
CuO	0.1	nd	nd	0.1	nd	nd	0.0	0.1
ZnO	nd	0.2	nd	nd	nd	0.2	0.1	0.1
As_2O_3	nd	nd	nd	0.1	nd	0.1	0.0	0.1
ZrO_2	1.6	1.8	1.6	2.4	1.7	2.5	1.9	0.4
MoO_3	3.4	2.9	2.7	3.5	3.1	3.5	3.2	0.3
SnO	13.0	15.1	16.0	16.4	15.1	13.0	14.8	1.5
Sb_2O_3	nd	0.1	nd	0.2	nd	nd	0.1	0.1
WO_3	8.0	10.2	7.5	13.3	8.6	15.5	10.5	3.2
Sum	101.8	101.7	101.1	102.5	101.7	102.4	101.9	

Trereife (Stable Hobba) 3/36

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.3	0.7	nd	0.2	0.5	0.3	0.3	0.2
MgO	0.2	0.5	nd	0.1	0.1	nd	0.2	0.2
Al_2O_3	10.1	10.5	7.0	7.7	10.5	10.8	9.4	1.6
SiO_2	24.3	24.2	21.3	26.6	27.6	25.7	25.0	2.2
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.1	1.3	1.1	1.5	1.2	1.3	1.3	0.2
CaO	1.8	1.5	1.3	1.8	1.7	1.5	1.6	0.2
TiO_2	1.8	1.5	1.2	1.0	1.5	1.8	1.5	0.3
V_2O_5	nd	0.1	nd	nd	nd	nd	0.0	0.0
MnO	0.3	0.5	0.5	0.5	0.3	0.4	0.4	0.1
FeO	28.3	33.0	26.7	31.3	28.7	28.2	29.4	2.3
CuO	0.1	0.1	nd	nd	nd	nd	0.0	0.1
ZnO	nd	nd	nd	0.2	nd	nd	0.0	0.1
As_2O_3	nd	nd	0.3	0.1	nd	nd	0.1	0.1
ZrO_2	1.6	1.7	3.1	1.7	1.6	2.1	2.0	0.6
MoO_3	2.5	2.9	3.6	2.3	3.5	3.6	3.1	0.6
SnO	13.8	13.6	11.6	14.1	15.8	13.3	13.7	1.4
Sb_2O_3	0.3	nd	0.2	0.1	nd	0.1	0.1	0.1
WO_3	10.2	9.5	24.6	12.2	8.4	13.1	13.0	5.9
Sum	96.7	101.6	102.5	101.4	101.4	102.2	101.0	

Trereife (Stable Hobba) 4/21

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.9	0.9	0.7	0.9	0.7	0.8	0.8	0.1
MgO	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.0
Al_2O_3	13.7	14.3	13.8	13.5	14.0	14.0	13.9	0.3
SiO_2	33.5	34.4	31.6	33.5	31.4	29.5	32.3	1.8
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.7	1.8	1.7	1.8	1.7	1.6	1.7	0.1
CaO	1.4	1.5	1.3	1.4	1.3	1.2	1.4	0.1
TiO_2	3.1	3.3	3.4	2.9	3.2	3.7	3.3	0.3
V_2O_5	nd	nd	nd	nd	0.1	nd	0.0	0.0
MnO	0.4	0.4	0.4	0.3	0.4	0.3	0.4	0.1
FeO	25.5	26.8	27.7	25.1	28.6	30.4	27.4	2.0
CuO	nd	nd	0.1	nd	nd	0.1	0.0	0.1
ZnO	nd	0.1	nd	nd	0.2	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.3	0.8	1.1	1.0	1.2	0.9	1.1	0.2
MoO_3	0.5	0.3	0.4	0.5	0.7	0.3	0.5	0.2
SnO	13.3	14.1	12.5	13.6	11.8	11.7	12.8	1.0
Sb_2O_3	0.2	0.1	nd	0.2	nd	0.1	0.1	0.1
WO_3	5.0	5.7	5.0	4.9	4.4	4.9	5.0	0.4
Sum	101.5	105.4	100.6	100.5	100.6	100.5	101.5	

Trevellas Porth, St Agnes 4/19

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.7	1.6	1.7	1.4	1.7	1.5	1.6	0.1
MgO	2.1	2.0	2.3	2.3	2.1	2.0	2.1	0.1
Al_2O_3	15.8	15.9	15.4	15.4	15.3	15.5	15.6	0.2
SiO_2	35.4	35.0	34.9	34.9	34.8	34.9	35.0	0.2
P_2O_5	0.4	0.5	0.4	0.6	0.7	0.6	0.5	0.1
K_2O	4.0	3.9	3.9	3.9	4.0	4.0	4.0	0.1
CaO	3.4	3.5	3.5	3.5	3.5	3.5	3.5	0.0
TiO_2	1.9	1.9	1.9	2.0	1.8	1.8	1.9	0.1
V_2O_5	nd	nd	0.1	nd	nd	0.1	0.0	0.1
MnO	1.2	1.2	1.4	1.3	1.2	1.3	1.3	0.1
FeO	17.3	16.5	17.8	17.1	17.7	17.6	17.3	0.5
CuO	0.1	nd	nd	0.1	0.1	nd	0.1	0.1
ZnO	nd	0.1	nd	nd	nd	0.1	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.4	0.3	0.6	0.2	0.5	0.5	0.4	0.1
MoO_3	0.2	0.1	0.3	0.2	0.3	0.2	0.2	0.1
SnO	15.8	16.7	14.7	16.8	14.5	14.8	15.6	1.0
Sb_2O_3	nd	0.4	0.5	0.1	0.3	0.2	0.3	0.2
WO_3	1.2	1.1	1.7	1.5	2.2	2.2	1.7	0.5
Sum	100.9	100.7	101.1	101.3	100.7	100.8	100.9	

Wallabrook 3/18

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.3	2.5	2.6	2.4	2.1	2.5	2.4	0.2
MgO	4.4	4.3	4.1	4.4	4.0	4.3	4.3	0.2
Al_2O_3	14.2	14.8	14.0	14.3	14.2	14.7	14.4	0.3
SiO_2	38.4	40.5	38.6	39.4	38.9	39.2	39.2	0.8
P_2O_5	0.3	0.3	0.7	0.2	0.2	-0.1	0.3	0.3
K_2O	1.1	1.2	1.2	1.2	1.4	1.2	1.2	0.1
CaO	0.8	0.9	0.7	0.8	0.8	0.9	0.8	0.1
TiO_2	12.1	9.4	10.8	9.9	9.9	10.4	10.4	1.0
V_2O_5	0.2	0.2	0.4	0.3	0.3	0.2	0.3	0.1
MnO	0.7	0.9	0.9	0.8	0.9	0.8	0.8	0.1
FeO	18.9	18.8	18.9	19.0	18.5	18.8	18.8	0.2
CuO	0.1	nd	nd	0.1	nd	nd	0.0	0.1
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	0.3	0.2	0.8	0.9	1.0	0.6	0.3
MoO_3	nd	nd	nd	0.3	0.3	0.2	0.1	0.2
SnO	6.7	6.4	6.7	6.8	6.9	5.6	6.5	0.5
Sb_2O_3	nd	nd	0.2	nd	0.1	nd	0.1	0.1
WO_3	0.5	0.1	0.6	0.1	nd	0.5	0.3	0.3
Sum	101.3	100.6	100.6	100.8	99.4	100.2	100.5	

Wapsworthy Newtake 2/29

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.8	1.5	1.4	1.6	1.5	1.6	1.6	0.1
MgO	2.7	2.4	2.4	2.3	2.4	2.6	2.5	0.2
Al_2O_3	12.1	11.7	11.9	11.8	11.7	11.9	11.9	0.2
SiO_2	37.0	35.6	35.6	36.3	35.8	36.9	36.2	0.6
P_2O_5	0.4	0.3	0.4	0.3	0.3	0.2	0.3	0.1
K_2O	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.0
CaO	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
TiO_2	8.2	8.7	8.7	8.9	8.6	8.8	8.7	0.2
V_2O_5	0.3	0.2	0.2	0.1	0.3	0.4	0.3	0.1
MnO	2.4	2.4	2.5	2.5	2.4	2.5	2.5	0.1
FeO	11.2	12.1	11.8	11.8	11.8	12.0	11.8	0.3
CuO	nd	0.1	nd	nd	nd	nd	nd	-
ZnO	nd	nd	0.1	nd	nd	0.2	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.1	0.1	nd	nd	nd	0.2	0.1	0.1
MoO_3	0.1	0.1	nd	nd	nd	nd	0.0	0.1
SnO	23.0	23.6	23.0	22.9	24.9	22.1	23.3	0.9
Sb_2O_3	nd	0.2	nd	nd	nd	nd	0.0	0.1
WO_3	0.1	0.1	1.0	0.4	nd	0.3	0.3	0.3
Sum	101.1	100.8	100.8	100.6	101.4	101.4	101.0	

Week Ford 4/23

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	3.2	3.1	3.2	3.1	3.1	2.9	3.1	0.1
MgO	4.7	4.8	4.9	4.4	4.8	4.6	4.7	0.2
Al_2O_3	18.8	18.7	18.5	17.5	18.7	17.9	18.4	0.5
SiO_2	45.5	45.6	44.2	42.4	45.1	43.3	44.4	1.3
P_2O_5	0.6	0.3	0.7	0.1	0.6	0.5	0.5	0.2
K_2O	1.6	1.7	1.5	1.3	1.5	1.5	1.5	0.1
CaO	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.1
TiO_2	6.2	6.1	5.8	5.6	6.0	6.2	6.0	0.2
V_2O_5	0.3	0.2	0.2	0.3	0.2	nd	0.2	0.1
MnO	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.1
FeO	12.3	12.0	12.9	11.6	12.3	11.2	12.1	0.6
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	0.1	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	3.1	4.0	2.9	4.1	3.5	4.1	3.6	0.5
MoO_3	nd	nd	nd	0.1	nd	nd	0.0	0.0
SnO	8.2	8.2	8.7	8.7	8.2	7.4	8.2	0.5
Sb_2O_3	nd	nd	0.2	nd	nd	0.2	0.1	0.1
WO_3	0.3	nd	0.8	0.9	0.4	0.2	0.4	0.4
Sum	105.7	105.7	105.6	101.1	105.5	101.2	104.1	

Weir Quay 2/18

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.4	1.4	1.0	1.5	1.2	1.2	1.3	0.2
MgO	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.0
Al_2O_3	14.2	14.4	14.9	14.5	14.3	14.5	14.5	0.2
SiO_2	34.5	34.6	34.9	33.9	34.3	34.9	34.5	0.4
P_2O_5	0.1	0.2	0.1	0.2	0.2	0.1	0.2	0.1
K_2O	2.4	2.4	2.5	2.7	2.4	2.5	2.5	0.1
CaO	1.7	1.6	1.7	1.5	1.5	1.7	1.6	0.1
TiO_2	2.2	2.1	2.2	2.1	2.2	2.2	2.2	0.1
V_2O_5	nd	nd	nd	0.1	0.1	nd	0.0	0.1
MnO	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0
FeO	20.7	20.6	21.0	21.5	20.7	21.0	20.9	0.3
CuO	0.1	nd	nd	nd	nd	nd	0.0	0.0
ZnO	0.1	0.3	0.1	0.1	0.1	nd	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.6	0.6	0.6	0.8	0.6	0.5	0.6	0.1
MoO_3	0.4	0.6	0.4	0.6	0.4	0.4	0.5	0.1
SnO	18.1	18.4	18.3	18.1	18.9	18.7	18.4	0.3
Sb_2O_3	0.1	0.1	nd	nd	nd	nd	0.0	0.1
WO_3	2.7	2.4	2.2	2.1	3.0	2.2	2.4	0.3
Sum	100.4	100.8	101.0	100.8	101.0	101.2	100.8	

Whitten Knowles 2/36

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.4	1.5	1.4	1.5	1.2	1.6	1.4	0.1
MgO	2.7	2.7	2.8	2.9	2.4	2.9	2.7	0.2
Al_2O_3	11.9	12.5	12.2	12.5	11.1	13.0	12.2	0.7
SiO_2	34.4	35.5	35.1	36.1	31.2	36.7	34.8	1.9
P_2O_5	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.1
K_2O	1.1	1.0	1.2	1.2	1.0	1.2	1.1	0.1
CaO	0.5	0.6	0.4	0.5	0.5	0.5	0.5	0.1
TiO_2	2.7	2.7	2.8	2.8	2.9	2.8	2.8	0.1
V_2O_5	nd	0.2	0.2	0.1	0.1	nd	0.1	0.1
MnO	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.1
FeO	11.4	11.3	10.9	11.0	10.7	11.4	11.1	0.3
CuO	nd	nd	nd	nd	nd	0.1	0.0	0.0
ZnO	nd	nd	0.3	nd	0.1	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.1	nd	0.4	0.3	0.3	0.2	0.1
MoO_3	0.1	nd	nd	nd	0.2	0.1	0.1	0.1
SnO	33.3	32.6	32.6	31.3	38.4	29.0	32.9	3.1
Sb_2O_3	0.1	0.1	nd	0.2	nd	nd	0.1	0.1
WO_3	0.4	nd	0.6	nd	0.2	0.5	0.3	0.2
Sum	100.8	101.4	101.0	101.0	100.9	100.9	101.0	

Lower Yealm Steps 2/13

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	0.2	0.1	0.6	2.4	0.5	0.3	0.7	0.9
MgO	1.7	0.9	0.6	0.9	0.7	0.8	0.9	0.4
Al_2O_3	7.9	9.8	7.1	7.5	7.7	7.0	7.8	1.0
SiO_2	21.0	19.0	20.1	19.8	18.2	19.2	19.6	1.0
P_2O_5	nd	0.1	nd	nd	0.1	nd	0.0	0.1
K_2O	0.4	0.5	0.6	0.7	0.4	0.5	0.5	0.1
CaO	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.1
TiO_2	0.7	1.0	1.0	1.0	1.3	0.7	1.0	0.2
V_2O_5	nd	nd	nd	0.2	nd	nd	0.0	0.1
MnO	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.1
FeO	43.8	39.7	33.4	31.2	35.0	34.2	36.2	4.7
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	0.2	0.2	0.2	nd	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.2	0.2	nd	0.4	0.3	0.6	0.3	0.2
MoO_3	0.1	nd	nd	nd	0.1	0.4	0.1	0.2
SnO	23.3	27.0	34.7	35.2	34.2	34.9	31.6	5.1
Sb_2O_3	0.3	0.4	nd	0.2	0.4	0.2	0.3	0.2
WO_3	nd	1.0	1.2	0.7	0.6	0.9	0.7	0.4
Sum	100.4	100.6	100.3	101.1	100.4	100.5	100.5	

Lower Yealm Steps 3/31

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.3	2.1	2.6	2.3	2.5	2.5	2.4	0.2
MgO	2.0	2.0	2.1	2.2	2.2	2.5	2.2	0.2
Al_2O_3	13.1	14.2	13.8	14.1	14.4	14.0	13.9	0.5
SiO_2	33.6	35.0	35.1	34.9	36.1	35.2	35.0	0.8
P_2O_5	nd	nd	0.1	nd	nd	nd	0.0	0.0
K_2O	1.1	1.2	0.9	1.2	1.1	1.0	1.1	0.1
CaO	0.3	0.6	0.7	0.6	0.5	0.6	0.6	0.1
TiO_2	4.5	4.9	4.9	4.8	5.3	4.8	4.9	0.3
V_2O_5	0.2	0.3	0.4	0.5	0.3	0.2	0.3	0.1
MnO	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.1
FeO	6.7	6.9	7.0	7.3	7.3	7.1	7.1	0.2
CuO	nd	nd	0.1	nd	nd	nd	0.0	0.0
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.7	1.0	0.5	0.7	0.7	0.5	0.7	0.2
MoO_3	0.2	0.4	0.1	0.1	0.4	0.1	0.2	0.1
SnO	33.7	29.7	30.1	30.9	28.0	29.4	30.3	1.9
Sb_2O_3	0.1	0.1	nd	0.1	nd	0.7	0.2	0.3
WO_3	2.6	1.9	1.9	1.3	1.6	2.0	1.9	0.4
Sum	101.5	100.7	100.6	101.4	100.8	100.9	101.0	

Lower Yealm Steps 3/32

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.2	2.3	2.1	2.4	1.9	2.2	0.2
MgO	3.2	3.3	3.4	2.9	3.4	2.9	3.2	0.2
Al_2O_3	16.0	16.4	16.9	16.4	16.2	16.8	16.5	0.3
SiO_2	39.2	39.8	41.5	40.3	39.1	40.5	40.1	0.9
P_2O_5	nd	0.1	0.5	nd	nd	nd	0.1	0.2
K_2O	1.6	1.4	1.7	1.7	1.6	1.7	1.6	0.1
CaO	0.9	1.0	0.9	1.0	0.7	0.9	0.9	0.1
TiO_2	2.7	3.3	3.3	3.6	3.3	3.3	3.3	0.3
V_2O_5	0.2	0.2	nd	nd	nd	0.2	0.1	0.1
MnO	0.4	0.2	0.4	0.4	0.3	0.3	0.3	0.1
FeO	6.6	6.8	7.1	6.8	6.8	6.5	6.8	0.2
CuO	nd	0.1	nd	nd	0.1	0.1	0.1	0.1
ZnO	nd	nd	nd	0.1	0.1	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	0.8	0.5	0.4	1.2	0.9	1.2	0.8	0.3
MoO_3	0.2	0.1	0.4	0.4	0.3	0.3	0.3	0.1
SnO	24.6	24.3	22.8	21.9	24.7	21.2	23.3	1.5
Sb_2O_3	0.3	nd	nd	nd	0.1	nd	0.1	0.1
WO_3	1.7	1.4	1.9	1.9	2.1	2.2	1.9	0.3
Sum	100.9	101.1	103.5	100.7	102.1	100.0	101.4	

Upper Yealm Steps 2/10

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.0	1.1	1.3	1.1	1.3	1.4	1.2	0.2
MgO	1.5	1.9	1.7	1.5	1.6	1.7	1.7	0.2
Al_2O_3	10.1	10.6	10.4	10.8	10.8	11.4	10.7	0.4
SiO_2	30.5	31.1	30.5	31.7	31.4	32.2	31.2	0.7
P_2O_5	nd	nd	nd	nd	nd	nd	nd	-
K_2O	1.7	1.6	1.6	1.8	1.6	2.0	1.7	0.2
CaO	2.4	2.3	2.3	2.5	2.4	2.2	2.4	0.1
TiO_2	5.3	5.2	5.0	5.4	5.1	6.2	5.4	0.4
V_2O_5	nd	nd	0.2	0.2	0.2	0.1	0.1	0.1
MnO	1.3	1.2	1.1	1.2	1.2	1.2	1.2	0.1
FeO	15.4	15.0	14.8	15.2	14.8	15.1	15.1	0.2
CuO	nd	nd	nd	nd	0.1	nd	0.0	0.0
ZnO	nd	nd	nd	0.1	nd	nd	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.8	1.8	1.9	1.8	1.7	1.6	1.8	0.1
MoO_3	1.0	0.9	1.0	1.0	1.0	0.8	1.0	0.1
SnO	18.8	18.8	18.9	16.8	19.6	18.5	18.6	0.9
Sb_2O_3	0.2	nd	nd	nd	nd	0.1	0.1	0.1
WO_3	11.2	10.9	11.6	10.9	10.4	10.2	10.9	0.4
Sum	102.2	102.4	102.3	102.0	103.2	104.7	102.8	

Yellowmead 2/44

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	2.5	2.6	2.4	2.6	2.3	2.4	2.5	0.1
MgO	3.6	3.8	3.8	3.7	3.7	3.7	3.7	0.1
Al_2O_3	17.8	18.1	18.2	17.9	17.8	18.1	18.0	0.2
SiO_2	41.8	42.5	42.1	42.2	41.6	42.0	42.0	0.3
P_2O_5	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.0
K_2O	3.3	3.3	3.3	3.4	3.3	3.3	3.3	0.0
CaO	1.4	1.3	1.4	1.3	1.4	1.4	1.4	0.1
TiO_2	5.5	5.6	5.7	5.7	5.7	5.7	5.7	0.1
V_2O_5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
MnO	1.9	1.7	1.7	1.8	1.8	1.8	1.8	0.1
FeO	9.2	8.8	9.2	9.0	9.0	9.0	9.0	0.2
CuO	nd	0.1	nd	nd	nd	nd	0.0	0.0
ZnO	0.2	nd	nd	nd	0.1	0.1	0.1	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.0	1.0	1.3	1.3	1.2	1.2	1.2	0.1
MoO_3	nd	nd	nd	0.3	0.1	nd	0.1	0.1
SnO	11.4	11.4	11.6	11.7	11.8	11.6	11.6	0.2
Sb_2O_3	nd	0.2	nd	0.2	0.1	nd	0.1	0.1
WO_3	0.6	0.3	nd	nd	0.6	0.7	0.4	0.3
Sum	101.0	101.5	101.5	101.8	101.3	101.8	101.5	

Yes Tor Bottom 2/60

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean	St Dev
Na_2O	1.9	2.0	2.2	2.1	1.9	2.2	2.1	0.1
MgO	2.7	2.8	2.8	2.7	2.7	2.8	2.8	0.1
Al_2O_3	15.9	16.0	15.8	16.1	15.3	16.0	15.9	0.3
SiO_2	39.7	39.5	39.5	40.4	38.2	39.6	39.5	0.7
P_2O_5	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.1
K_2O	1.6	1.6	1.6	1.6	1.6	1.5	1.6	0.0
CaO	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.1
TiO_2	4.3	4.3	4.4	4.3	4.4	4.5	4.4	0.1
V_2O_5	0.3	0.1	0.3	0.4	0.2	0.2	0.3	0.1
MnO	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.1
FeO	11.7	11.4	11.9	11.7	11.8	11.6	11.7	0.2
CuO	nd	nd	nd	nd	nd	nd	nd	-
ZnO	nd	nd	nd	nd	nd	nd	nd	-
As_2O_3	nd	nd	nd	nd	nd	nd	nd	-
ZrO_2	1.5	1.4	1.6	1.4	1.6	1.7	1.5	0.1
MoO_3	nd	nd	nd	0.1	nd	nd	0.0	0.0
SnO	19.6	19.7	19.6	18.9	22.1	19.5	19.9	1.1
Sb_2O_3	nd	0.2	0.1	nd	nd	0.1	0.1	0.1
WO_3	0.3	0.5	0.4	0.4	0.7	0.2	0.4	0.1
Sum	100.8	100.7	101.4	101.3	101.5	101.1	101.1	

For analysis of slags from High Down and East Okement see Appendix 13.

Appendix 5: Chemical Composition of Flow Bands (wt%)

Analysis carried out using EDX-SEM. Elements with higher concentrations in the lighter of a pair of bands are shaded yellow; in the dark band they are shaded pink. nd = not detected

	Avon Dam 2/20		Caerloggas 3/44		Caerloggas 3/45	
Oxide	**Light 1**	**Dark 1**	**Light 1**	**Dark 1**	**Light 1**	**Dark 1**
Na_2O	2.0	2.6	1.1	1.4	1.3	1.5
MgO	3.8	3.6	1.7	1.8	2.0	2.1
Al_2O_3	16.8	16.8	11.3	12.4	13.2	15.6
SiO_2	40.4	43.5	20.7	22.7	26.1	28.6
P_2O_5	0.2	0.7	nd	nd	0.1	0.0
K_2O	1.6	2.0	0.7	0.9	0.8	0.9
CaO	0.9	1.1	0.7	0.7	0.7	0.6
TiO_2	4.2	8.1	1.4	1.4	1.8	1.8
V_2O_5	0.2	0.4	0.0	0.0	nd	nd
MnO	0.4	0.4	0.5	0.4	0.5	0.5
FeO	10.7	9.1	4.3	4.3	4.7	5.0
CuO	0.1	0.1	0.0	0.2	0.1	nd
ZnO	0.1	0.2	nd	0.0	0.0	nd
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	1.2	1.4	0.6	0.5	0.2	0.4
MoO_3	0.4	nd	0.2	0.3	0.1	0.2
SnO	15.9	10.6	49.0	42.5	41.8	35.7
Sb_2O_3	nd	0.0	0.7	0.7	0.0	nd
WO_3	2.5	0.6	2.1	2.7	3.5	3.5
Sum	101.4	101.2	95.0	92.7	97.0	96.6

	Crift Farm 4/15				Crift Farm 4/16			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	3.6	2.9	2.4	2.7	2.2	2.7	2.4	2.3
MgO	3.9	4.6	3.7	4.2	4.1	4.5	4.0	4.1
Al_2O_3	19.7	20.2	17.1	19.5	19.0	20.6	19.0	19.3
SiO_2	41.9	46.5	40.9	43.7	39.5	42.1	39.9	40.5
P_2O_5	nd	0.3	nd	nd	nd	nd	0.0	0.1
K_2O	1.3	1.9	1.6	1.5	1.3	1.5	1.3	1.3
CaO	0.8	1.2	1.3	1.0	1.2	1.2	1.1	1.2
TiO_2	2.1	2.9	2.7	2.2	2.2	2.3	2.0	2.2
V_2O_5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
MnO	0.3	0.3	0.4	0.2	0.2	0.4	0.2	0.3
FeO	6.3	8.8	8.9	5.8	5.8	5.8	5.9	6.0
CuO	0.0	0.0	0.0	0.0	0.0	0.1	nd	nd
ZnO	nd	nd	nd	0.2	0.0	nd	nd	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.4	nd	0.2	0.1	0.1	0.2	0.3	0.0
MoO_3	0.1	0.2	0.2	0.3	nd	0.0	0.0	nd
SnO	20.1	9.8	19.3	18.6	23.6	18.0	23.6	21.7
Sb_2O_3	0.1	0.4	0.0	0.3	0.0	0.2	nd	0.3
WO_3	0.9	1.6	2.5	0.8	2.0	1.8	1.5	1.8
Sum	101.5	101.6	101.2	101.1	101.3	101.5	101.3	101.1

	Crift Farm 4/17				Crift Farm 4/27	
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**
Na_2O	2.1	2.4	2.3	2.5	2.1	2.5
MgO	3.3	3.4	3.1	3.6	3.1	3.6
Al_2O_3	22.7	24.9	23.7	24.5	19.8	20.1
SiO_2	38.9	42.4	37.8	43.0	40.8	42.8
P_2O_5	nd	nd	nd	nd	0.1	0.0
K_2O	1.4	1.6	1.3	1.6	1.2	1.3
CaO	1.0	0.9	0.9	1.1	1.0	1.2
TiO_2	2.3	2.4	2.0	2.8	2.7	2.8
V_2O_5	0.0	0.0	nd	0.0	0.0	0.1
MnO	0.2	0.4	0.4	0.3	0.1	0.2
FeO	6.3	6.5	6.3	6.4	8.9	8.3
CuO	0.0	0.0	0.0	0.1	nd	0.0
ZnO	nd	0.1	nd	nd	nd	nd
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	0.5	0.5	0.6	0.1	0.1	0.2
MoO_3	0.0	0.2	0.1	0.0	0.0	nd
SnO	18.2	10.1	19.1	11.3	21.1	17.2
Sb_2O_3	0.2	0.3	0.1	0.1	0.1	0.3
WO_3	1.5	1.0	1.4	1.3	0.2	0.9
Sum	98.6	97.3	98.8	98.5	101.3	101.4

	Ditsworthy 3/01				Doe Tor Green 2/12			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.7	1.9	1.3	1.6	2.2	2.3	2.2	2.3
MgO	1.8	1.7	1.5	1.8	3.1	3.6	3.9	4.0
Al_2O_3	13.4	15.1	12.4	14.5	15.1	15.9	16.0	16.5
SiO_2	33.2	38.1	31.1	35.9	39.2	42.7	42.7	45.3
P_2O_5	0.2	0.1	0.2	0.1	0.3	0.6	0.3	0.1
K_2O	2.5	3.2	2.1	2.9	1.3	1.6	1.4	1.6
CaO	1.9	2.1	1.7	1.9	0.7	0.7	0.7	0.7
TiO_2	5.7	6.2	5.0	6.3	6.7	8.3	7.9	7.9
V_2O_5	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1
MnO	0.5	0.4	0.4	0.5	0.7	0.8	0.8	0.7
FeO	8.1	8.1	7.8	8.5	11.1	10.8	10.7	10.0
CuO	nd	0.1	0.1	0.1	nd	nd	0.0	nd
ZnO	0.2	0.0	0.1	0.0	nd	0.0	0.0	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.7	0.6	0.6	0.6	4.2	5.2	4.9	4.6
MoO_3	0.0	nd	0.1	0.1	0.0	0.0	0.1	nd
SnO	30.4	22.3	35.8	25.1	15.7	7.6	8.7	6.2
Sb_2O_3	nd	0.2	nd	0.0	0.0	nd	nd	0.3
WO_3	0.9	0.4	0.2	0.3	0.7	1.0	1.1	0.8
Sum	101.4	100.7	100.6	100.4	101.1	101.2	101.6	101.1

	Hurdon 2/01				Hurdon 4/26			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.1	1.3	1.2	1.5	1.1	1.1	0.7	1.0
MgO	2.3	2.9	2.5	3.0	1.2	1.5	1.1	1.1
Al_2O_3	10.6	12.0	10.5	12.7	10.6	11.7	10.1	11.0
SiO_2	29.1	32.7	29.6	34.2	30.1	32.5	28.3	31.1
P_2O_5	nd	nd	nd	nd	nd	nd	nd	nd
K_2O	1.5	1.7	1.4	1.8	1.0	1.4	1.0	1.2
CaO	2.4	2.5	2.4	2.7	0.6	0.6	0.6	0.5
TiO_2	4.7	5.1	4.8	5.7	3.6	3.8	3.5	3.9
V_2O_5	0.0	0.3	0.0	0.1	0.1	0.0	nd	0.1
MnO	2.2	2.6	2.3	2.8	3.0	3.1	2.8	3.0
FeO	9.9	10.1	9.8	10.5	8.1	8.0	7.4	8.1
CuO	nd	0.1	0.0	nd	nd	nd	nd	nd
ZnO	0.0	0.1	nd	nd	nd	nd	nd	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	0.1	0.0
ZrO_2	2.4	1.8	2.1	1.7	2.5	2.1	2.4	2.4
MoO_3	1.3	0.8	0.9	0.8	1.3	1.1	1.1	1.2
SnO	20.5	14.9	19.6	12.7	23.9	20.7	28.4	21.0
Sb_2O_3	0.4	0.3	0.0	0.1	nd	0.1	0.1	nd
WO_3	14.0	12.8	15.3	11.6	15.8	14.7	15.1	17.1
Sum	102.4	102.0	102.4	101.9	102.9	102.4	102.7	102.7

	Longstone 2/06				Longstone 4/24			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.6	2.3	2.1	2.3	1.6	2.4	1.6	1.8
MgO	2.8	3.8	3.4	3.8	2.4	2.9	2.4	2.5
Al_2O_3	13.4	17.1	15.4	17.4	13.1	15.2	12.6	13.5
SiO_2	33.5	42.2	38.6	44.6	33.7	38.4	32.6	35.6
P_2O_5	nd	0.1	0.3	0.2	0.5	0.5	0.3	0.5
K_2O	1.0	1.5	1.6	1.7	0.9	1.1	0.8	1.2
CaO	0.3	0.5	0.5	0.6	0.6	0.5	0.6	0.6
TiO_2	2.7	3.4	3.0	3.4	4.9	4.3	4.0	4.2
V_2O_5	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.2
MnO	0.2	0.3	0.1	0.2	0.4	0.4	0.3	0.3
FeO	7.2	8.5	7.4	7.8	7.1	6.3	6.7	6.5
CuO	0.0	0.0	nd	0.0	0.0	0.0	0.1	0.1
ZnO	0.0	nd	0.1	nd	0.0	0.0	0.1	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	1.1	1.2	0.9	1.0	0.3	0.2	0.5	0.3
MoO_3	0.1	0.1	0.0	0.0	0.0	0.2	0.2	0.1
SnO	36.5	19.8	26.9	18.3	35.2	28.5	37.6	33.0
Sb_2O_3	nd	0.3	0.0	0.2	nd	nd	nd	0.3
WO_3	0.8	nd	0.6	nd	nd	nd	0.3	0.0
Sum	101.3	101.2	101	101.6	100.8	101.2	100.8	100.7

	Upper Merrivale 2/24				Upper Merrivale 2/26			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.7	1.8	1.2	1.6	1.2	1.3	1.1	1.4
MgO	3.0	3.1	2.5	3.0	3.4	3.7	3.3	3.5
Al_2O_3	13.9	14.1	13.2	13.9	17.6	18.6	17.6	18.7
SiO_2	38.5	38.8	36.4	38.5	36.8	38.6	37.3	38.6
P_2O_5	0.3	0.1	0.0	0.3	0.3	0.4	0.2	0.0
K_2O	0.9	0.8	0.8	0.8	1.2	1.2	1.1	1.2
CaO	0.8	1.0	0.9	1.2	0.6	0.7	0.5	0.7
TiO_2	3.1	3.0	2.8	3.0	3.0	3.0	3.0	3.1
V_2O_5	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1
MnO	3.9	3.8	3.9	4.0	0.4	0.5	0.4	0.4
FeO	12.3	12.5	11.9	12.3	18.8	18.4	19.0	18.5
CuO	0.1	0.1	0.0	nd	0.0	0.0	0.0	nd
ZnO	nd	0.0	nd	0.1	nd	0.1	0.1	nd
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	nd	0.2	0.3	0.1	0.3	0.2	0.3	0.5
MoO_3	nd	0.1	0.3	0.0	0.3	0.2	0.3	0.3
SnO	21.8	20.2	25.0	21.2	15.0	12.4	14.9	12.3
Sb_2O_3	nd	0.0	0.1	0.0	0.4	0.1	0.1	0.0
WO_3	1.1	1.0	1.1	0.9	1.4	1.5	1.7	1.5
Sum	101.5	100.7	100.6	101.1	100.8	101.1	101	100.8

	Upper Merrivale 2/53				Upper Merrivale 3/24	
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**
Na_2O	3.5	3.4	3.8	3.7	1.9	2.0
MgO	4.5	4.5	4.6	4.3	2.9	3.2
Al_2O_3	18.6	18.6	18.3	19.1	14.8	15.8
SiO_2	49.2	49.4	49.0	50.3	39.1	41.4
P_2O_5	0.4	0.4	0.1	0.5	nd	nd
K_2O	1.5	1.6	1.5	1.7	1.6	2.0
CaO	0.9	0.8	0.7	0.7	0.8	0.7
TiO_2	2.8	2.7	2.6	2.2	5.6	5.7
V_2O_5	0.1	0.2	0.2	0.1	0.1	0.2
MnO	0.7	0.6	0.7	0.6	1.0	1.0
FeO	11.4	11.4	11.4	10.5	11.5	11.1
CuO	nd	nd	0.0	nd	0.0	0.0
ZnO	nd	0.2	0.2	0.0	0.1	nd
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	0.2	0.2	0.3	nd	1.5	1.3
MoO_3	0.2	0.0	0.1	nd	0.3	0.4
SnO	6.8	6.9	7.3	7.5	15.5	13.2
Sb_2O_3	0.2	0.0	0.1	0.1	0.0	0.0
WO_3	0.6	0.5	0.4	0.4	4.0	3.4
Sum	101.6	101.4	101.3	101.7	100.7	101.4

	Retallack 4/01		Retallack 4/02		Retallack 4/03		Trevellas Porth 4/19	
Oxide	**Light 1**	**Dark 1**	**Light 1**	**Dark 1**	**Light 1**	**Dark 1**	**Light 1**	**Dark 1**
Na_2O	1.9	2.1	1.7	1.7	1.8	1.7	1.9	1.6
MgO	1.6	2.0	1.4	1.5	1.3	1.5	2.3	2.3
Al_2O_3	14.1	15.7	12.7	13.6	11.8	12.1	16.1	15.9
SiO_2	35.7	38.9	39.7	43.0	32.4	32.9	35.7	35.7
P_2O_5	0.4	0.3	0.1	0.0	0.4	0.3	0.6	0.5
K_2O	3.8	4.3	3.0	3.7	3.0	3.4	4.0	4.0
CaO	3.7	4.3	4.2	4.4	3.2	3.5	3.5	3.5
TiO_2	0.8	1.1	1.0	0.9	0.4	0.5	1.8	1.9
V_2O_5	0.1	0.1	0.0	0.1	0.2	0.0	0.0	0.2
MnO	0.2	0.4	0.4	0.5	0.2	0.4	1.2	1.3
FeO	11.9	12.0	12.7	11.2	8.1	8.3	17.9	18.1
CuO	nd	0.1	nd	nd	0.0	nd	0.0	0.0
ZnO	0.2	0.1	nd	0.2	nd	nd	0.0	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	0.0	0.0
ZrO_2	0.4	0.2	0.2	0.1	0.1	0.0	0.6	0.5
MoO_3	0.1	0.2	0.2	0.1	0.1	nd	0.3	0.3
SnO	23.6	17.9	19.3	12.4	36.8	34.7	14.0	13.7
Sb_2O_3	0.4	0.3	0.4	0.4	0.1	0.7	0.0	0.0
WO_3	2.1	1.5	1.1	1.7	1.1	1.7	1.6	1.6
Sum	101.0	101.5	98.1	95.5	101.1	101.6	101.3	101.2

	Wapsworthy 2/29				Whitten Knowles 2/36			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.4	2.0	1.4	1.7	1.6	2.2	1.3	1.8
MgO	2.5	2.6	2.4	2.4	2.6	3.2	2.4	2.6
Al_2O_3	11.8	12.9	11.3	11.8	11.2	14.2	11.1	12.9
SiO_2	35.7	39.2	33.8	35.4	31.8	40.2	30.0	38.1
P_2O_5	0.3	0.3	0.3	0.2	0.4	0.4	0.6	0.4
K_2O	0.7	0.9	0.8	0.6	0.9	1.3	0.7	1.7
CaO	0.9	1.0	1.1	0.9	0.5	0.6	0.5	0.5
TiO_2	8.3	8.9	8.4	8.6	2.7	3.0	2.8	2.5
V_2O_5	0.4	0.3	0.2	0.3	0.2	0.3	0.1	0.1
MnO	2.4	2.5	2.3	2.4	0.3	0.1	0.1	0.2
FeO	11.6	11.5	11.3	12.2	11.0	11.2	10.8	9.2
CuO	0.0	0.0	0.0	0.1	0.0	nd	0.0	0.0
ZnO	0.1	nd	0.1	0.0	nd	nd	0.1	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.1	0.2	0.1	0.4	0.2	0.2	0.1	0.2
MoO_3	0.1	nd	0.2	0.3	nd	0.0	nd	0.1
SnO	23.7	18.9	27.0	23.9	37.6	24.4	40.3	30.2
Sb_2O_3	0.1	nd	0.2	0.0	0.0	nd	nd	0.3
WO_3	0.6	0.3	nd	nd	nd	nd	0.1	0.2
Sum	100.7	101.5	100.9	101.2	101.0	101.3	101.0	101.0

	Lower Yealm Steps 3/31				Lower Yealm Steps 3/32			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	2.6	2.5	2.8	2.5	2.1	2.2	1.9	2.1
MgO	2.5	2.3	2.3	2.4	3.3	3.0	3.1	3.6
Al_2O_3	14.2	15.5	13.8	13.7	15.9	17.1	15.4	17.4
SiO_2	36.1	39.3	35.2	34.8	38.9	43.0	37.7	43.0
P_2O_5	nd	nd	nd	nd	0.0	nd	0.2	0.0
K_2O	1.0	1.2	1.1	1.1	1.7	1.9	1.4	1.7
CaO	0.7	0.6	0.5	0.7	1.0	0.8	1.0	1.0
TiO_2	4.8	5.4	4.9	5.0	2.9	3.5	2.9	3.7
V_2O_5	0.3	0.2	0.2	0.3	0.1	0.4	0.1	0.1
MnO	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.3
FeO	7.0	7.4	7.0	6.8	6.8	6.9	7.1	7.2
CuO	0.0	nd	nd	0.0	0.0	0.0	0.0	0.2
ZnO	nd	nd	0.2	0.0	0.1	nd	nd	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.9	1.0	0.7	0.7	0.4	1.0	0.4	0.6
MoO_3	0.4	0.3	nd	0.1	0.1	0.5	0.2	0.1
SnO	28.8	23.6	30.2	30.4	25.1	18.9	26.6	18.7
Sb_2O_3	0.1	nd	nd	0.5	0.2	nd	0.4	nd
WO_3	1.5	1.2	2.1	1.7	2.0	1.6	2.1	1.5
Sum	101.2	101.0	101.4	101.1	100.9	101.2	101.0	101.3

	Yes Tor Bottom 2/60			
Oxide	**Light 1**	**Dark 1**	**Light 2**	**Dark 2**
Na_2O	1.8	1.9	2.0	2.0
MgO	2.7	2.9	2.7	3.0
Al_2O_3	15.9	16.1	16.2	16.6
SiO_2	39.5	40.3	39.8	40.9
P_2O_5	0.3	0.4	0.3	0.4
K_2O	1.4	1.7	1.6	1.7
CaO	0.5	0.5	0.5	0.5
TiO_2	4.5	4.5	4.4	4.2
V_2O_5	0.1	0.2	0.2	0.2
MnO	0.4	0.3	0.4	0.3
FeO	12.0	11.8	11.8	11.7
CuO	0.2	0.0	nd	0.0
ZnO	0.1	0.0	nd	0.1
As_2O_3	nd	nd	nd	nd
ZrO_2	1.7	1.7	1.7	1.8
MoO_3	nd	0.1	0.0	0.0
SnO	19.1	18.2	19.1	17.0
Sb_2O_3	0.1	0.1	nd	0.0
WO_3	0.6	0.5	0.5	0.7
Sum	100.9	101.2	101.2	101.1

Figure A5.1: Graph showing differences in Al_2O_3 content between pairs of flow bands in slags from different sites

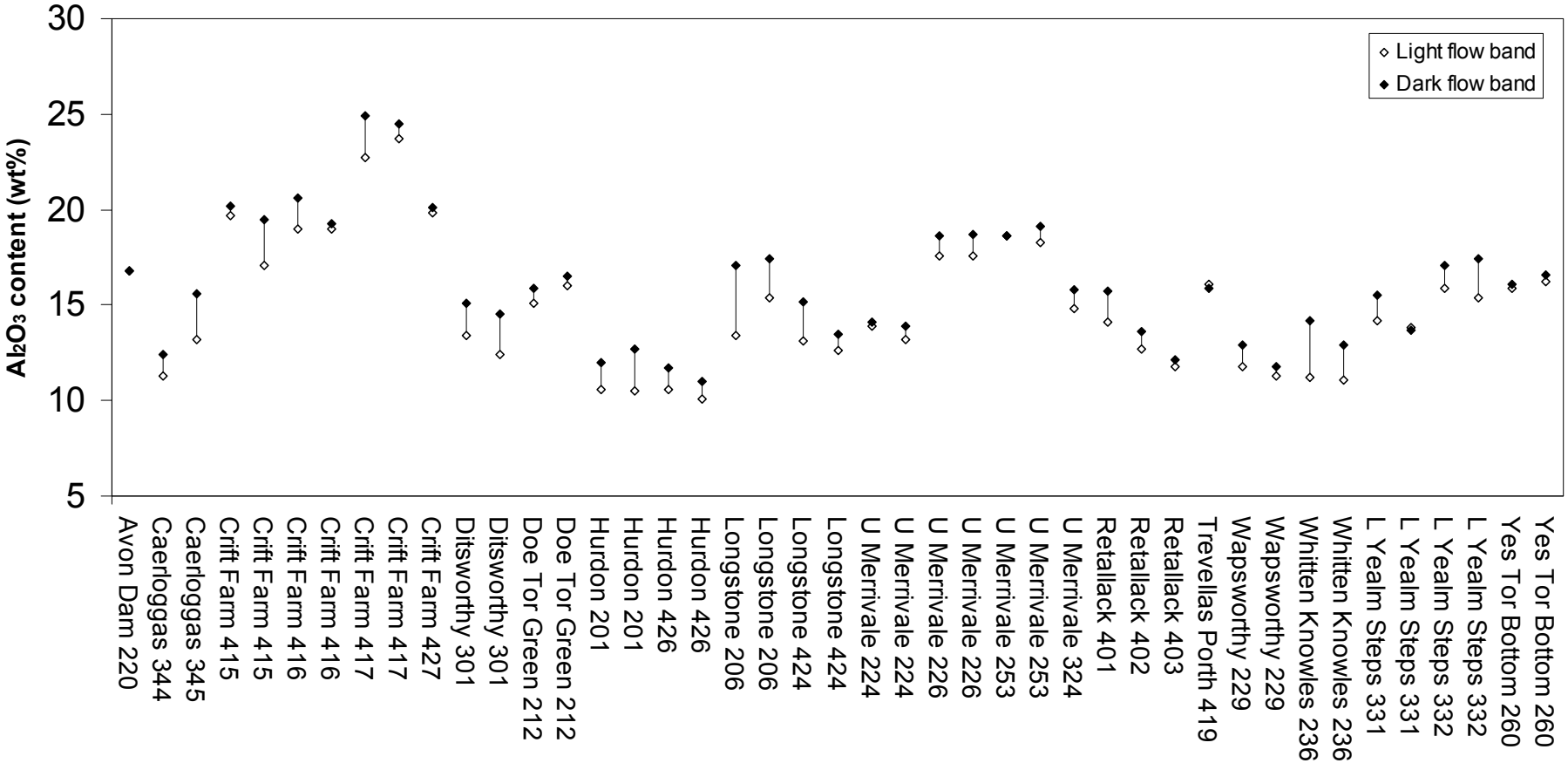


Figure A5.2: Graph showing differences in SiO_2 content between pairs of flow bands in slags from different sites

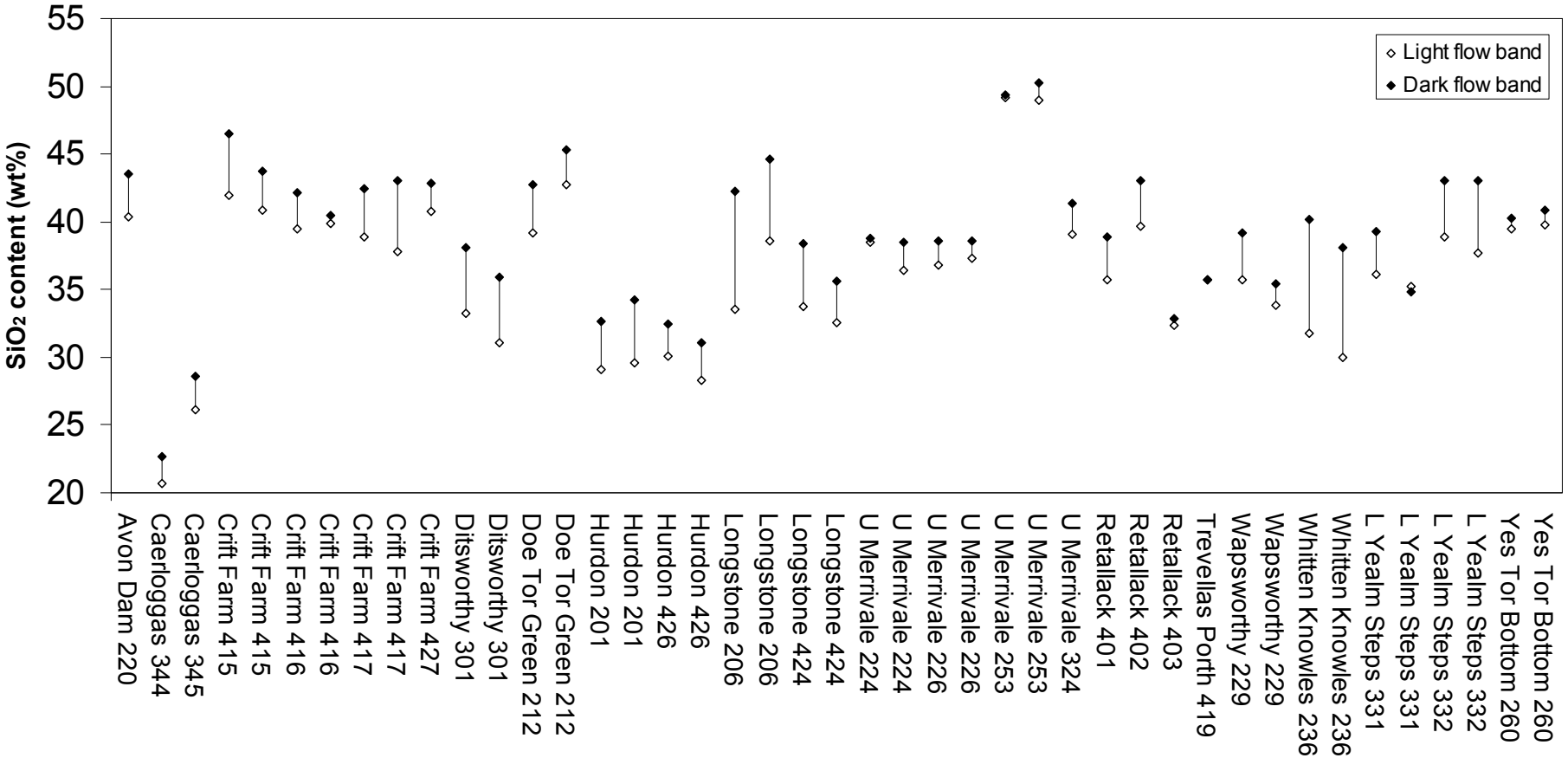


Figure A5.3: Graph showing differences in TiO_2 content between pairs of flow bands in slags from different sites

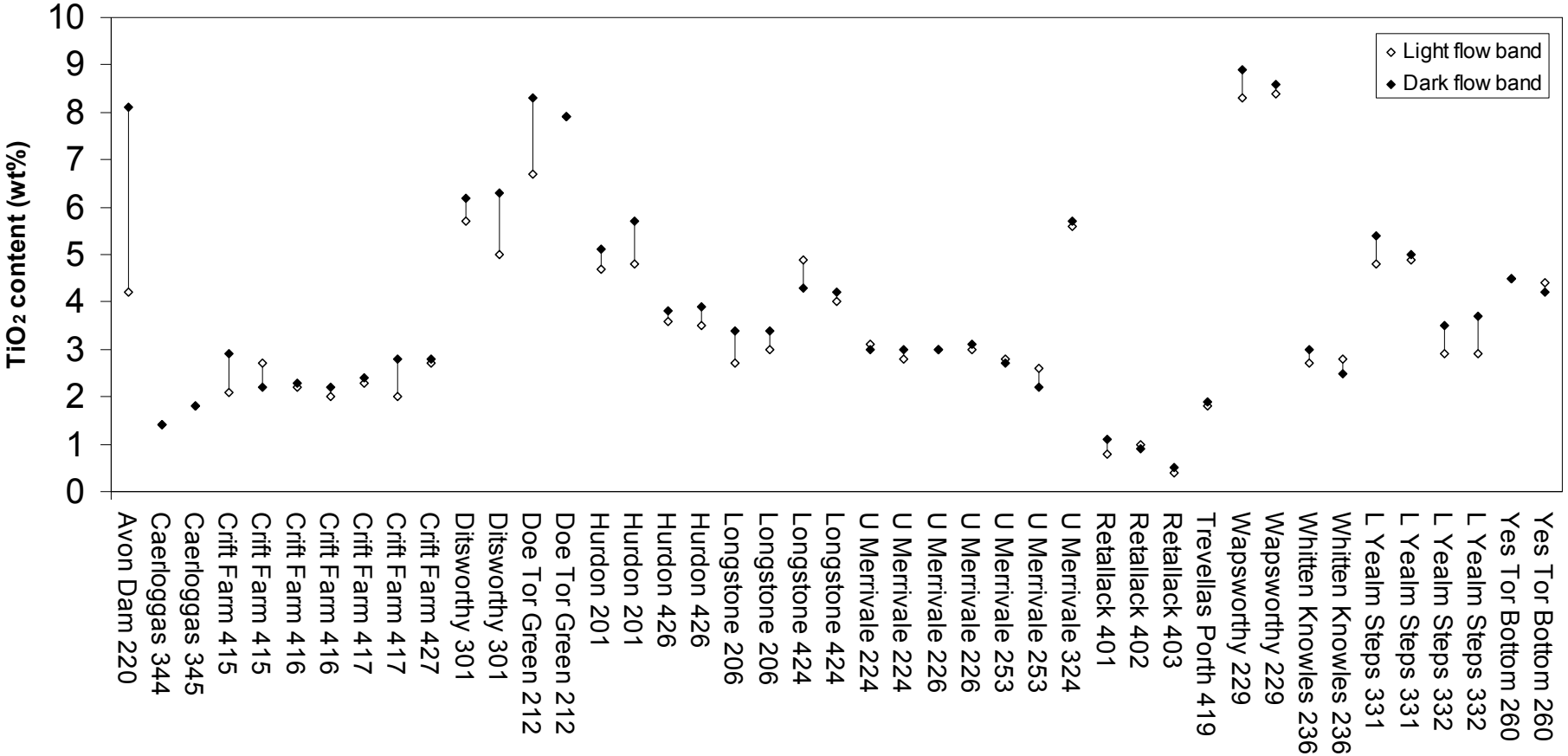


Figure A5.4: Graph showing differences in FeO content between pairs of flow bands in slags from different sites

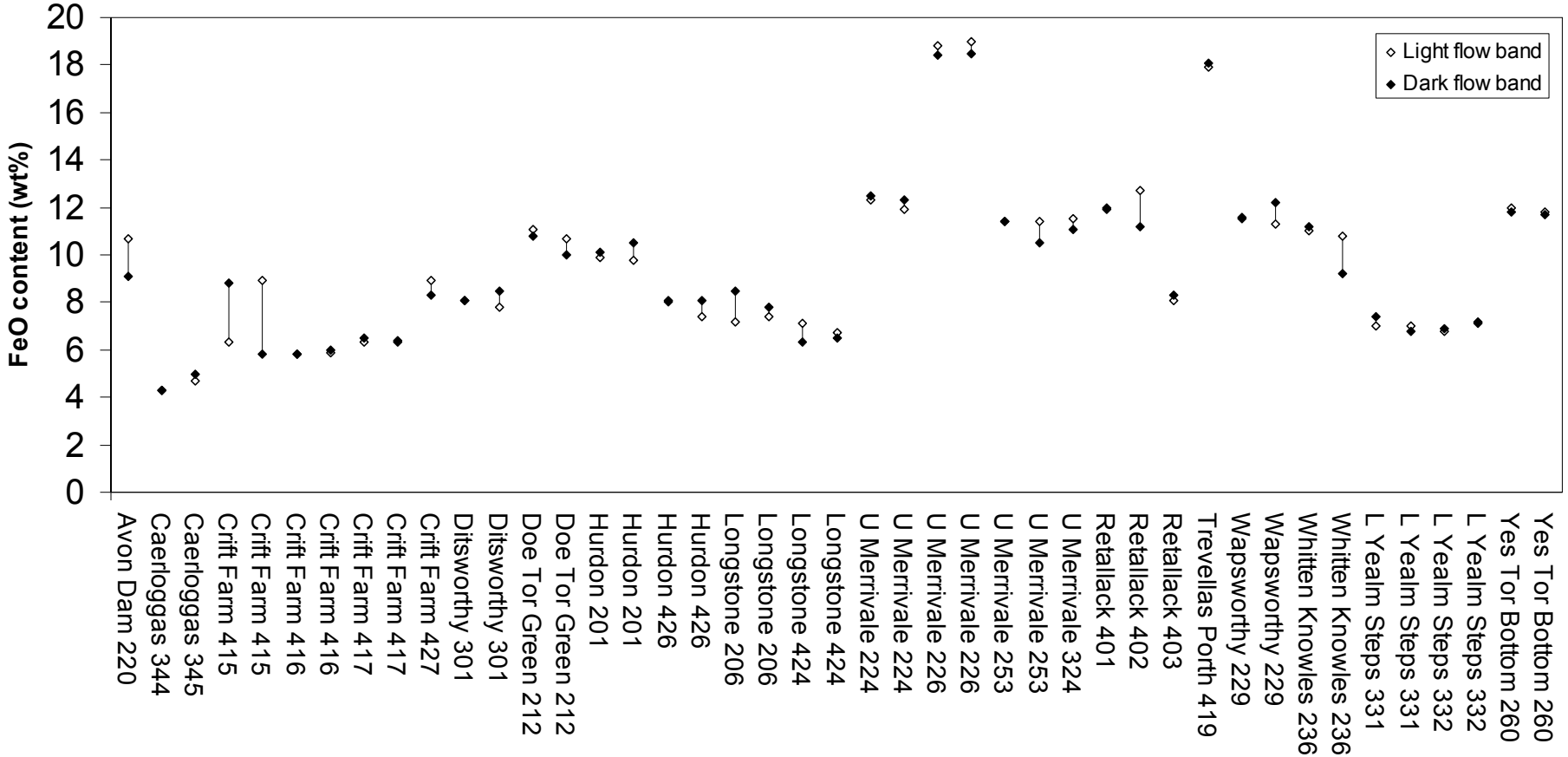


Figure A5.5: Graph showing differences in SnO content between pairs of flow bands in slags from different sites

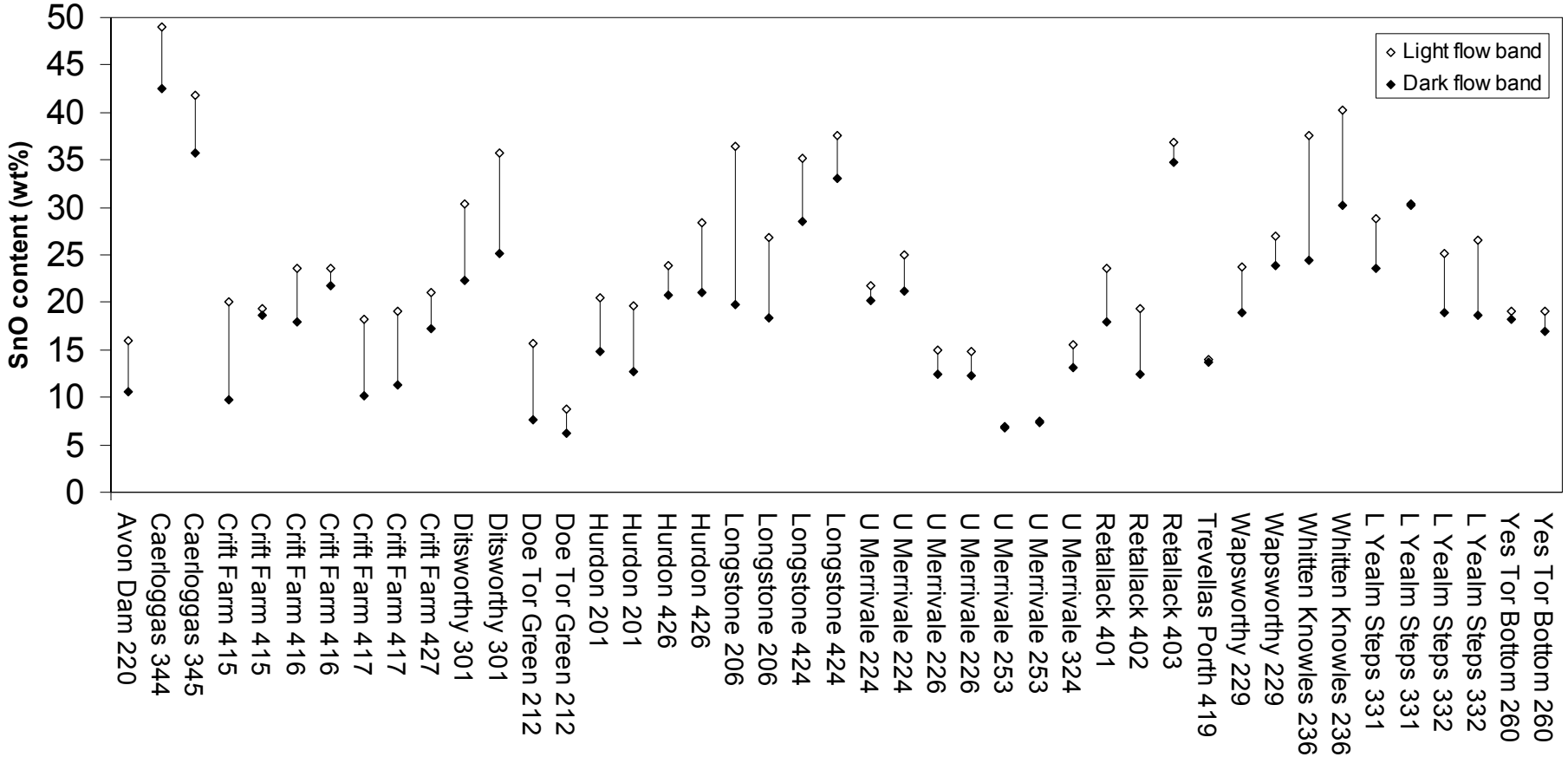
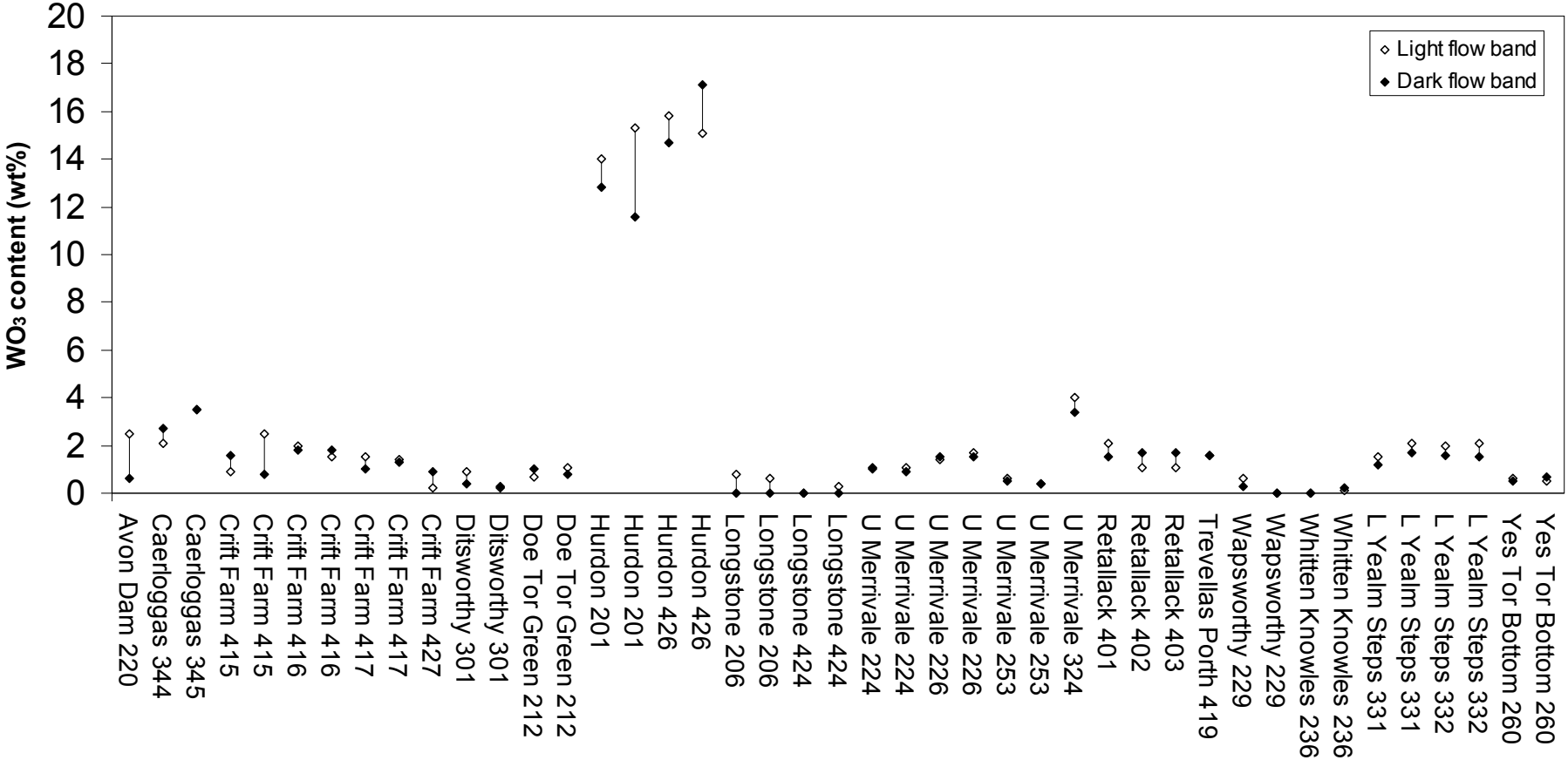


Figure A5.6: Graph showing differences in WO_3 content between pairs of flow bands in slags from different sites



Appendix 6: Chemical Composition of Feathery/Needle Phases (wt%)

Analysis carried out using EDX-SEM. Elements with higher concentrations in the light feathery phase are shaded yellow; in the surrounding dark matrix they are shaded pink. nd = not detected

	Avon Dam 2/20		Butterbrook 2/34				Gobbett 2/28	
Oxide	**Feather 1**	**Matrix 1**	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**	**Feather 1**	**Matrix 1**
Na_2O	1.1	2.9	0.8	2.2	0.6	1.9	0.3	1.5
MgO	5.0	3.8	2.3	2.5	1.8	2.6	3.6	3.0
Al_2O_3	10.0	17.1	9.9	15.8	3.9	16.1	5.3	13.6
SiO_2	12.8	43.6	27.1	39.6	8.4	39.4	13.4	38.0
P_2O_5	0.0	0.3	nd	nd	nd	nd	0.0	0.5
K_2O	0.7	1.9	1.5	1.9	0.5	1.9	0.5	1.3
CaO	0.4	1.2	0.7	1.1	0.2	1.0	0.3	0.8
TiO_2	49.5	8.2	17.0	2.2	40.7	1.9	34.5	3.3
V_2O_5	5.2	0.3	0.5	0.0	0.8	0.1	0.6	0.0
MnO	0.3	0.4	0.8	0.6	0.7	0.8	0.8	0.5
FeO	10.6	9.1	29.3	21.8	37.8	21.2	32.4	14.5
CuO	nd	0.2	0.0	0.0	0.1	0.1	0.0	0.1
ZnO	nd	0.0	0.0	nd	0.0	0.0	0.1	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	2.9	1.6	1.1	1.2	0.8	1.4	0.6	0.4
MoO_3	nd	nd	0.2	0.3	0.2	0.5	nd	0.1
SnO	2.6	10.5	6.5	8.8	1.9	8.6	8.2	22.5
Sb_2O_3	0.2	0.1	0.1	nd	0.0	0.0	0.2	0.2
WO_3	nd	0.1	3.3	3.3	2.0	3.7	0.0	0.8
Sum	101.3	101.3	101.2	101.3	100.6	101.1	100.8	101.1

	Upper Merrivale 2/55		Nosworthy 3/16				Nosworthy 3/17			
Oxide	**Feather 1**	**Matrix 1**	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**
Na_2O	1.3	1.4	nd	1.7	0.5	2.0	0.5	1.1	1.5	1.5
MgO	2.8	2.9	3.4	2.6	3.6	2.8	2.1	2.2	2.1	2.2
Al_2O_3	11.2	11.4	3.8	11.9	2.4	13.2	2.8	10.5	10.4	12.7
SiO_2	31.5	32.7	3.0	33.2	2.4	35.8	6.0	29.6	28.2	33.8
P_2O_5	0.1	0.1	nd	0.2	nd	0.3	0.1	0.2	0.2	0.1
K_2O	0.9	1.1	0.4	1.5	0.2	1.4	0.6	1.3	1.4	1.9
CaO	1.0	0.9	0.1	1.0	0.1	1.0	0.3	1.1	0.8	1.3
TiO_2	3.9	3.2	52.5	5.4	48.8	1.8	45.9	4.3	14.6	1.7
V_2O_5	0.1	0.0	1.1	0.0	1.1	0.1	1.1	0.1	0.4	nd
MnO	1.1	1.1	0.7	1.6	1.5	1.3	1.5	1.7	1.3	1.4
FeO	15.0	14.5	26.2	19.6	34.3	16.4	32.8	23.7	22.7	18.4
CuO	0.0	0.0	0.0	0.0	nd	nd	0.0	nd	0.2	nd
ZnO	0.1	nd	0.1	nd	0.0	0.0	nd	nd	nd	nd
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	2.9	3.0	3.9	2.1	3.1	2.4	2.5	1.9	1.2	2.1
MoO_3	0.4	0.2	nd	0.2	nd	0.3	nd	0.3	0.1	0.3
SnO	24.6	25.0	4.5	19.0	2.4	20.9	4.2	21.0	14.1	21.8
Sb_2O_3	0.0	0.1	0.3	0.0	0.3	nd	nd	0.0	0.2	nd
WO_3	3.5	3.2	0.8	1.0	nd	1.4	0.3	1.8	1.3	1.6
Sum	100.4	100.8	100.8	101.1	100.8	101.0	100.6	101.0	100.7	100.9

	Outer Down 4/18						South Hill 2/43			
Oxide	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**	**Feather 3**	**Matrix 3**	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**
Na_2O	0.2	2.0	nd	4.0	0.6	2.2	1.9	2.1	2.2	2.6
MgO	1.5	1.3	1.4	1.3	1.2	1.3	2.9	2.8	2.9	2.8
Al_2O_3	2.6	14.8	1.8	15.3	4.7	14.7	14.6	15.2	14.8	15.1
SiO_2	6.4	41.6	4.2	42.5	10.4	41.4	40.3	43.5	40.4	43.6
P_2O_5	nd	0.5	nd	0.1	nd	0.2	0.2	0.2	0.4	0.2
K_2O	0.5	3.4	0.5	3.7	0.8	3.1	2.2	2.3	2.0	2.6
CaO	0.4	1.8	0.3	1.9	0.3	2.1	1.1	1.2	1.2	0.9
TiO_2	45.0	1.3	46.9	1.2	41.3	2.5	10.4	7.6	9.0	8.7
V_2O_5	0.5	0.0	0.7	0.0	0.7	0.0	0.3	0.1	0.2	0.2
MnO	1.0	0.4	1.1	0.6	1.0	0.6	1.2	1.1	1.3	0.9
FeO	39.4	13.7	40.9	13.1	35.7	15.4	15.9	15.6	17.0	15.1
CuO	nd	0.0	0.0	0.0	nd	0.0	0.1	nd	0.0	nd
ZnO	nd	0.1	nd	0.0	0.1	0.1	0.0	nd	nd	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.6	0.6	0.8	0.7	0.5	0.6	1.2	0.9	0.9	0.8
MoO_3	0.0	0.0	0.0	0.1	0.0	0.0	0.4	0.0	0.0	0.2
SnO	2.5	18.9	2.0	16.3	2.5	15.8	6.9	7.6	7.1	6.2
Sb_2O_3	nd	0.0	0.1	nd	0.1	nd	0.0	0.1	nd	nd
WO_3	nd	0.5	nd	0.4	0.4	0.9	1.1	0.7	1.5	1.4
Sum	100.6	100.9	100.7	101.2	100.3	100.9	100.7	101	100.9	101.4

	Stannon Brook 2/02				Taw River 2/15			
Oxide	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**	**Feather 1***	**Matrix 1**	**Feather 2***	**Matrix 2**
Na_2O	1.0	1.5	1.5	1.3	0.9	1.5	nd	1.4
MgO	2.2	2.6	2.5	2.7	4.0	2.4	5.6	2.4
Al_2O_3	5.3	13.0	9.7	12.7	4.8	10.4	1.5	9.9
SiO_2	11.3	41.4	28.6	40.7	10.6	26.4	3.0	25.2
P_2O_5	0.0	0.1	nd	0.1	nd	nd	nd	nd
K_2O	0.6	2.2	1.8	2.3	0.3	0.7	0.1	0.8
CaO	0.2	1.1	0.4	1.1	0.2	0.8	0.1	0.8
TiO_2	59.1	11.0	34.9	10.3	36.6	1.5	47.9	2.1
V_2O_5	1.4	0.0	0.8	0.2	0.7	0.0	0.6	0.1
MnO	0.3	0.9	0.5	0.9	2.3	1.0	2.7	1.1
FeO	17.6	20.2	16.7	20.9	27.2	7.9	32.7	7.8
CuO	0.0	0.0	0.0	nd	nd	0.1	0.0	nd
ZnO	nd	nd	nd	0.0	nd	0.0	nd	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.4	0.1	0.3	0.0	1.6	2.2	1.2	2.8
MoO_3	0.0	0.1	0.0	0.0	0.2	0.4	0.0	0.3
SnO	1.1	6.3	3.3	7.3	11.9	36.7	3.4	33.5
Sb_2O_3	0.2	nd	nd	0.2	0.2	0.2	0.0	0.4
WO_3	nd	0.4	0.1	0.3	2.8	7.2	0.8	7.4
Sum	100.7	100.9	101.1	101.0	104.3	99.4	99.7	96.1

*Feather phases in Taw River 2/15 appear dark compared to surrounding matrix

	Taw River 2/40		Taw River 2/41			
Oxide	**Needle 1**	**Matrix 1**	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**
Na_2O	1.2	0.9	1.5	2.1	1.8	2.2
MgO	2.2	2.8	2.5	5.1	5.1	4.8
Al_2O_3	8.0	9.4	9.6	14.6	10.4	14.9
SiO_2	26.9	29.0	28.3	40.4	27.2	42.3
P_2O_5	nd	nd	nd	0.6	0.1	nd
K_2O	1.0	1.0	1.2	1.4	1.5	1.6
CaO	0.5	0.7	0.7	1.1	0.5	1.2
TiO_2	8.8	8.2	28.8	7.0	32.5	6.4
V_2O_5	0.3	0.0	0.6	0.1	0.8	0.0
MnO	1.5	1.6	0.8	1.3	0.8	1.2
FeO	11.8	12.1	9.0	13.4	11.9	12.2
CuO	nd	0.0	nd	nd	nd	0.0
ZnO	nd	nd	nd	0.1	0.0	nd
As_2O_3	0.2	nd	nd	nd	nd	nd
ZrO_2	5.6	5.0	7.0	1.7	2.9	2.5
MoO_3	1.3	0.7	nd	nd	nd	0.1
SnO	15.2	20.8	6.3	9.5	5.0	9.3
Sb_2O_3	0.0	0.1	nd	0.2	0.0	nd
WO_3	18.7	9.9	6.5	3.0	1.0	2.4
Sum	103.2	102.2	102.8	101.6	101.5	101.1

	Wallabrook 3/18				Week Ford 4/23		Yellowmead 2/44	
Oxide	**Feather 1**	**Matrix 1**	**Feather 2**	**Matrix 2**	**Feather 1**	**Matrix 1**	**Feather 1**	**Matrix 1**
Na_2O	nd	1.9	0.0	2.6	2.8	3.0	1.9	2.9
MgO	4.1	4.0	4.5	3.9	3.2	5.0	3.3	3.7
Al_2O_3	4.6	15.0	4.9	15.3	10.9	19.5	17.5	18.1
SiO_2	3.6	41.0	0.5	42.1	27.1	45.5	40.9	42.0
P_2O_5	nd	0.3	nd	0.3	0.0	0.3	0.7	0.6
K_2O	0.2	1.1	0.0	1.3	1.2	1.6	3.6	3.4
CaO	0.1	0.7	0.1	0.9	0.4	0.7	1.5	1.4
TiO_2	63.8	4.0	70.0	3.9	21.5	5.3	6.3	5.5
V_2O_5	1.4	0.1	2.4	0.0	0.9	0.1	0.2	0.2
MnO	0.4	0.9	0.3	0.7	0.2	0.4	1.9	1.9
FeO	19.0	19.3	16.7	18.3	8.0	13.0	10.3	8.8
CuO	0.1	0.0	nd	nd	nd	nd	0.1	0.0
ZnO	0.0	0.0	0.2	0.3	0.0	0.0	nd	nd
As_2O_3	0.0	nd	nd	nd	nd	nd	nd	nd
ZrO_2	1.1	0.5	0.9	0.6	20.9	1.8	1.1	1.2
MoO_3	nd	nd	0.0	0.1	nd	0.1	0.2	0.1
SnO	1.0	7.7	0.1	7.3	4.2	8.4	11.8	11.1
Sb_2O_3	nd	nd	0.0	nd	0.2	0.2	0.1	0.0
WO_3	nd	0.1	0.2	0.5	0.5	0.1	nd	0.3
Sum	99.5	96.7	100.8	98.1	101.9	105.0	101.4	101.2

Figure A6.1: Graph showing differences in Al_2O_3 content between feathery/needle-like phases and slag matrix in slags from different sites

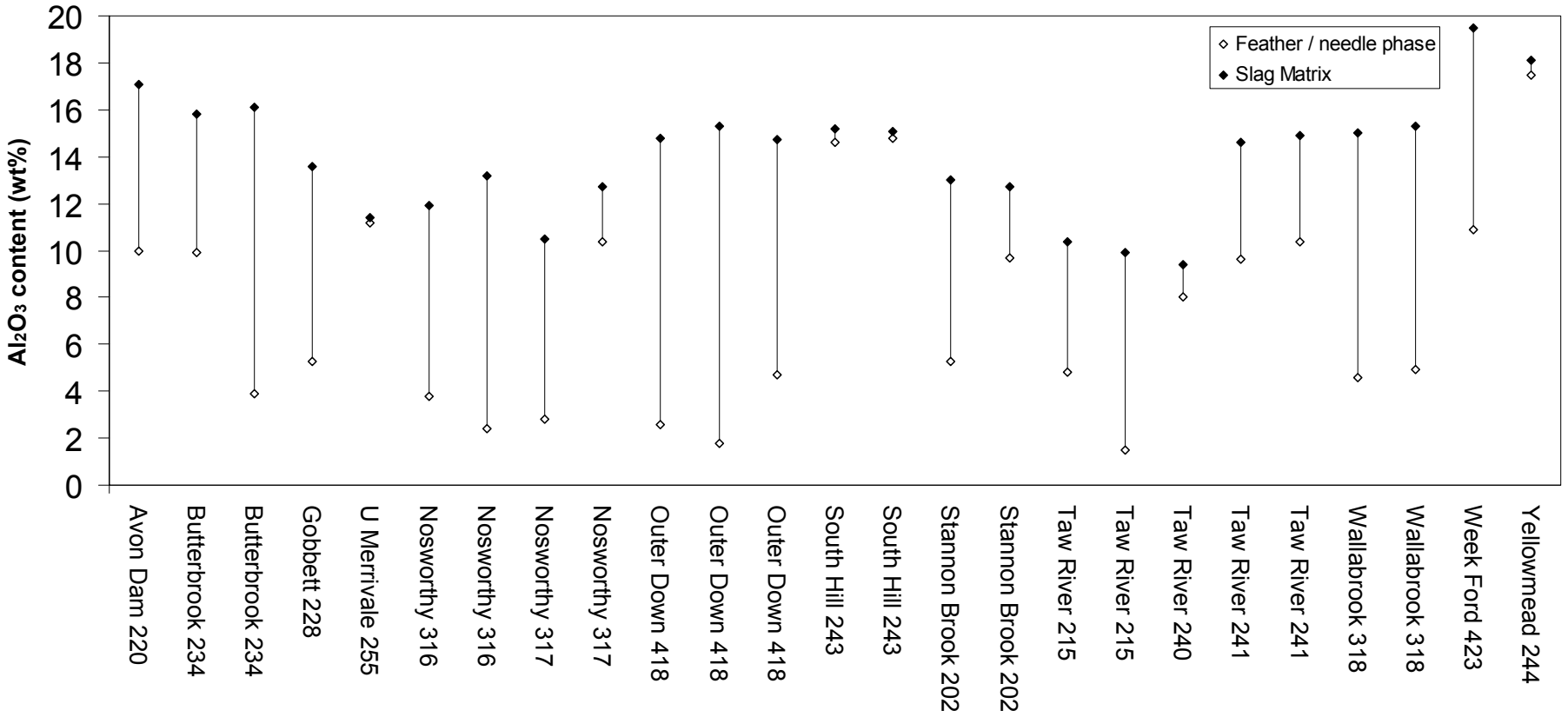


Figure A6.2: Graph showing differences in SiO_2 content between feathery/needle-like phases and slag matrix in slags from different sites

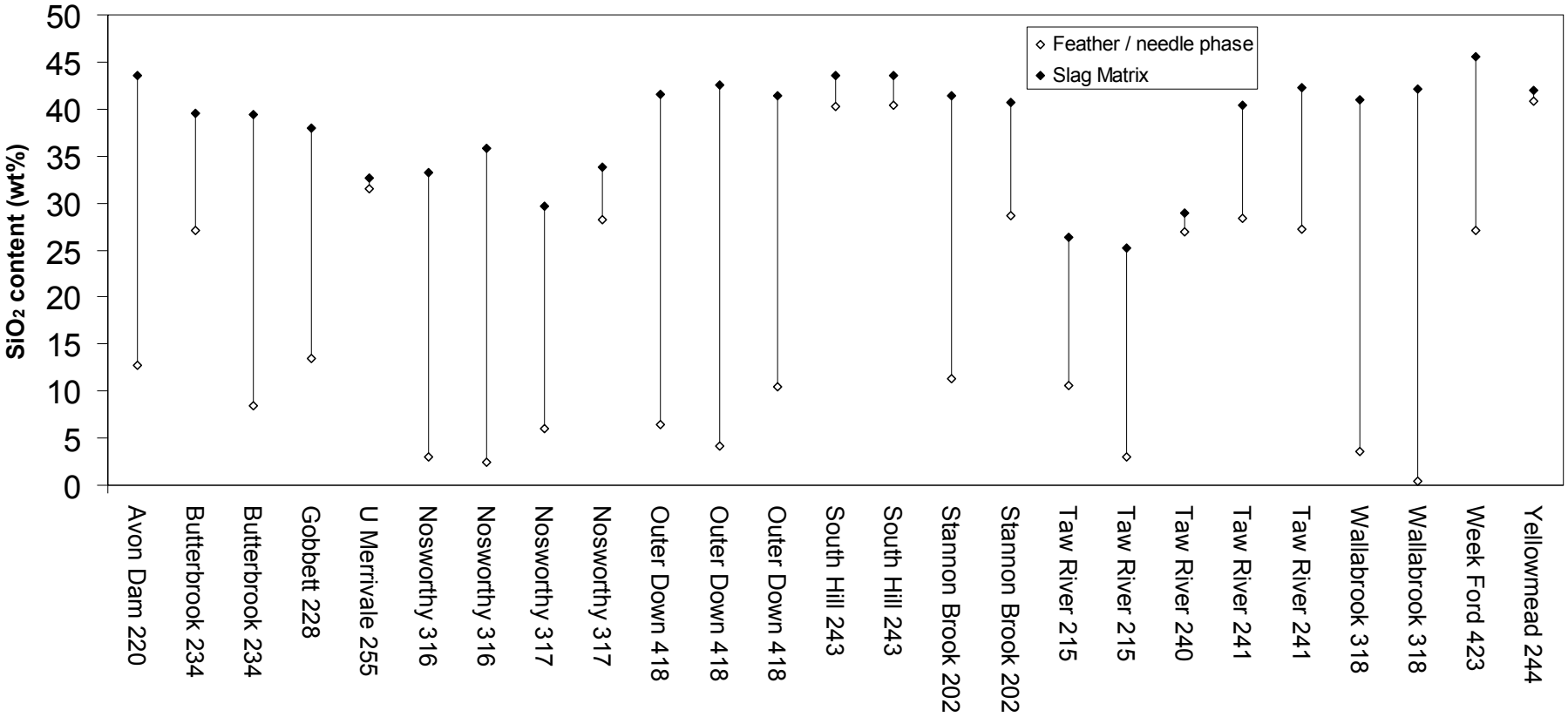


Figure A6.3: Graph showing differences in TiO_2 content between feathery/needle-like phases and slag matrix in slags from different sites

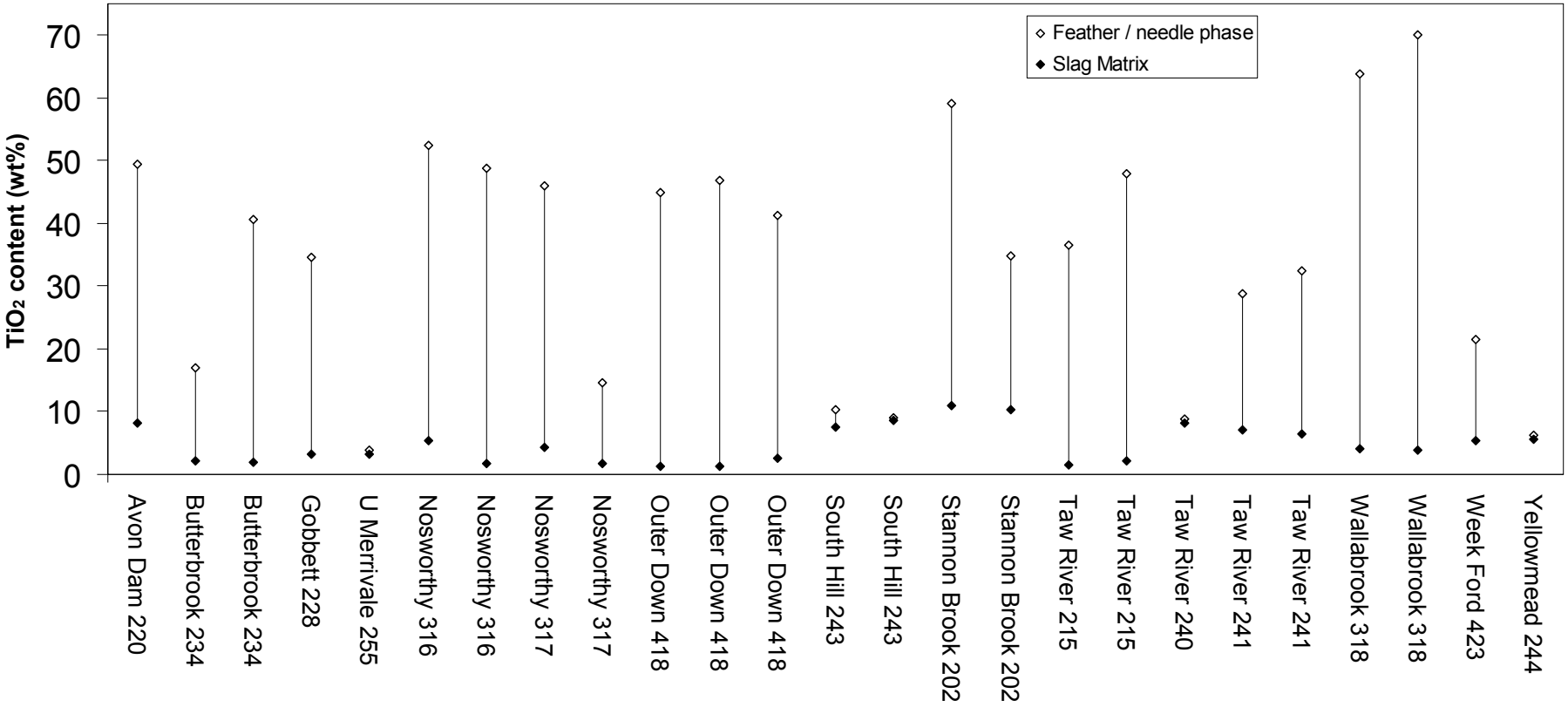


Figure A6.4: Graph showing differences in FeO content between feathery/needle-like phases and slag matrix in slags from different sites

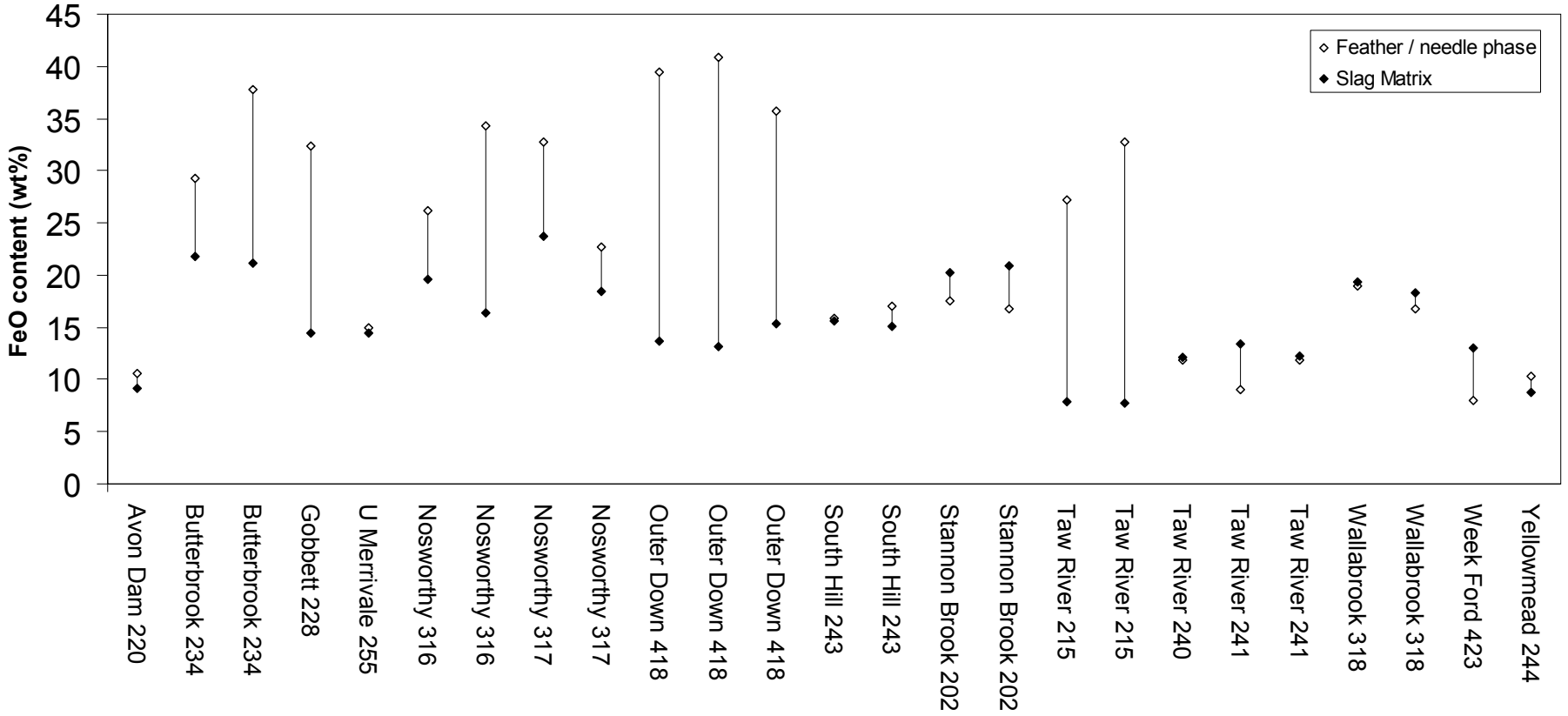


Figure A6.5: Graph showing differences in SnO content between feathery/needle-like phases and slag matrix in slags from different sites

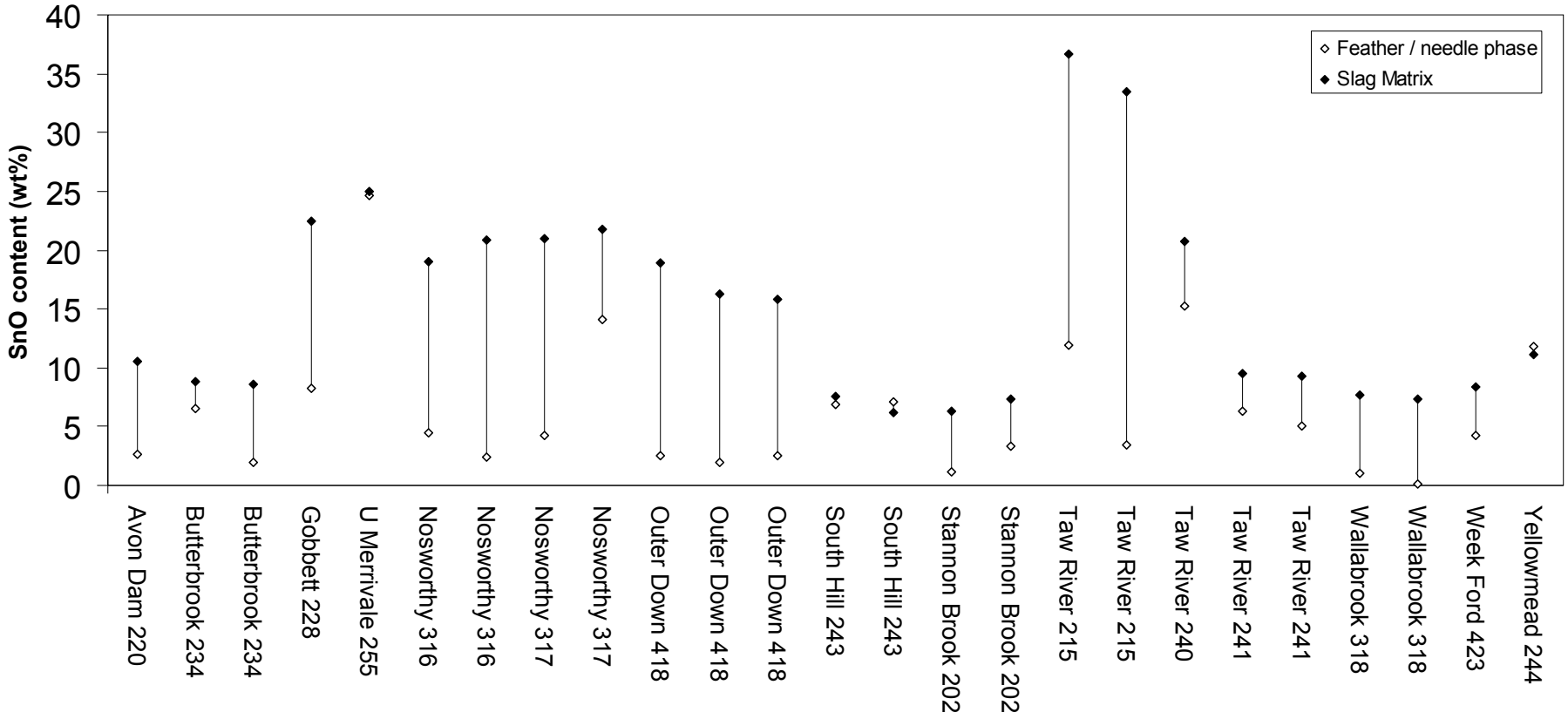
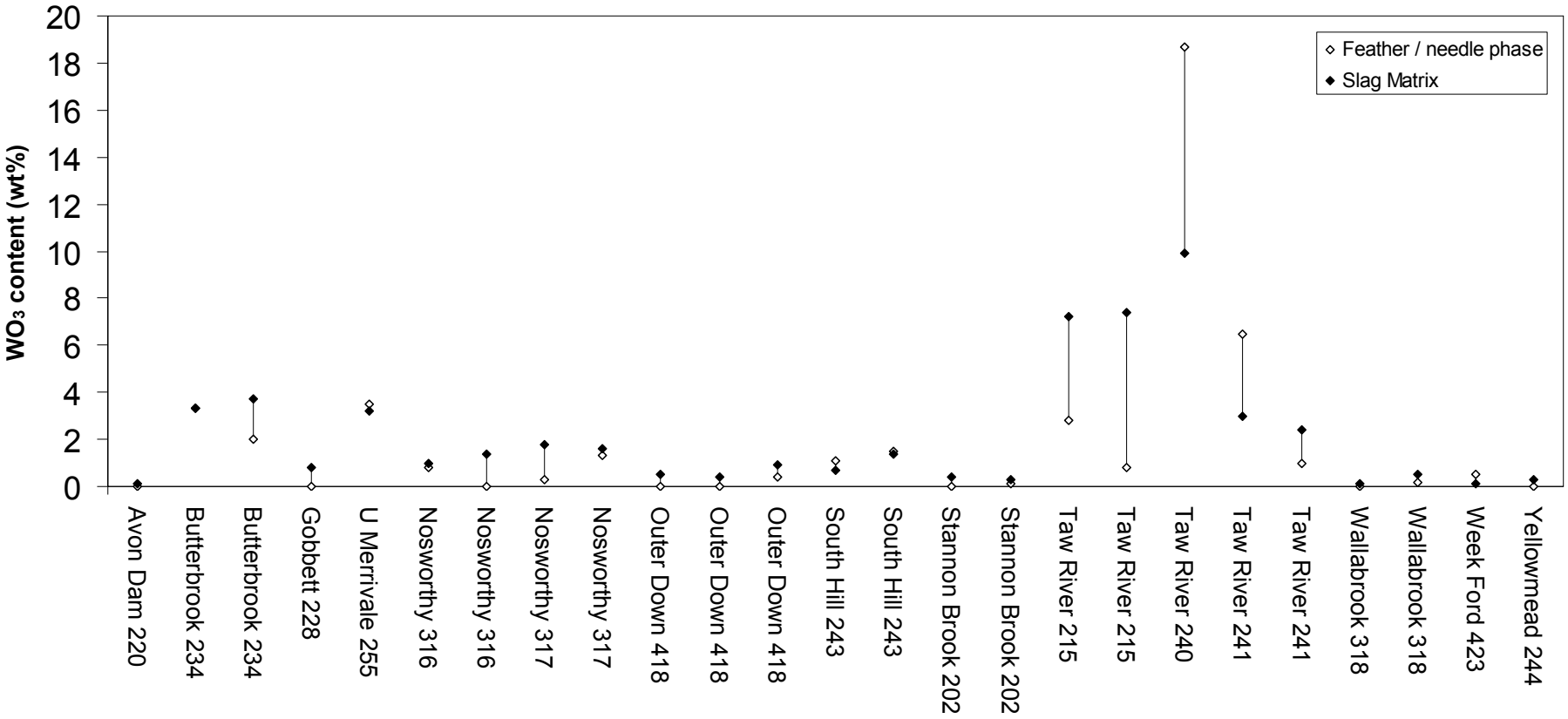


Figure A6.6: Graph showing differences in WO_3 content between feathery/needle-like phases and slag matrix in slags from different sites



Appendix 7: Chemical Composition of Dendrites (wt%)

Analysis carried out using EDX-SEM. Elements with higher concentrations in the dendrites are shaded yellow; in the surrounding matrix they are shaded pink. nd = not detected

	Blackaller 4/22		Drakeford Bridge 2/19				Eylesbarrow 2/35	
Oxide	**Dendrite 1**	**Matrix 1**	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**	**Dendrite 1**	**Matrix 1**
Na_2O	nd	2.6	0.9	2.4	2.0	2.1	nd	2.8
MgO	1.8	4.0	1.2	1.3	1.4	1.3	4.1	0.6
Al_2O_3	11.3	17.0	8.1	11.9	12.7	13.5	42.7	17.4
SiO_2	0.7	42.0	16.1	28.9	38.7	40.8	0.8	64.5
P_2O_5	0.0	3.0	0.3	0.0	0.5	0.7	0.0	nd
K_2O	0.1	1.9	1.5	3.1	3.9	4.3	0.0	4.7
CaO	0.1	3.2	0.6	1.1	3.1	3.0	0.1	3.3
TiO_2	4.4	1.2	21.1	13.4	4.6	4.3	1.3	2.1
V_2O_5	0.2	0.1	0.4	0.3	nd	0.0	0.2	0.0
MnO	0.2	0.3	1.0	0.8	0.6	0.7	0.3	0.0
FeO	70.2	18.7	45.6	31.5	16.7	13.9	51.8	4.2
CuO	nd	0.0	0.0	0.0	nd	0.2	0.0	nd
ZnO	0.0	nd	nd	0.0	nd	0.1	0.1	0.0
As_2O_3	0.1	nd	nd	nd	nd	nd	nd	nd
ZrO_2	nd	0.0	0.2	0.3	0.6	0.3	0.0	0.5
MoO_3	nd	0.1	0.0	0.1	0.1	0.1	nd	0.2
SnO	10.4	9.9	3.4	5.5	14.3	14.1	0.0	0.7
Sb_2O_3	0.0	0.1	0.1	0.2	0.3	0.0	nd	0.2
WO_3	nd	2.0	nd	nd	1.1	1.3	0.1	0.1
Sum	99.5	106.1	100.5	100.8	100.6	100.7	101.5	101.3

	Lingcombe 3/20				Lustleigh 2/50			
Oxide	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**
Na_2O	nd	2.4	nd	2.7	1.9	1.9	1.7	1.9
MgO	1.5	1.5	1.5	1.5	1.6	1.4	1.3	1.4
Al_2O_3	4.4	12.4	5.7	12.4	15.0	15.5	12.6	15.1
SiO_2	0.8	44.4	3.4	45.4	35.9	36.8	28.7	36.5
P_2O_5	0.0	0.2	0.1	0.4	0.4	0.4	0.2	0.2
K_2O	0.0	2.7	0.2	3.2	2.9	2.8	2.4	2.8
CaO	0.1	2.8	0.2	2.7	3.2	3.3	2.4	3.4
TiO_2	28.6	3.0	27.3	2.2	3.1	0.9	11.1	0.7
V_2O_5	0.4	0.0	0.6	0.2	0.1	0.1	0.2	0.1
MnO	1.7	1.0	1.5	1.0	2.1	2.1	2.1	2.2
FeO	62.0	16.9	59.7	15.8	21.7	20.4	24.9	20.7
CuO	0.0	0.0	0.0	0.0	0.0	0.0	nd	0.0
ZnO	nd	nd	nd	0.1	nd	0.0	0.2	0.0
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.3	1.7	0.5	0.8	0.2	0.0	0.1	0.2
MoO_3	0.1	0.1	nd	nd	0.2	0.1	nd	0.0
SnO	0.6	11.3	0.8	11.4	13.2	13.9	11.6	14.7
Sb_2O_3	0.1	nd	0.1	0.3	0.0	0.3	0.1	0.0
WO_3	0.1	0.8	nd	0.9	nd	0.9	0.9	0.6
Sum	100.7	101.2	101.4	101.0	101.5	100.8	100.5	100.5

	Lustleigh 2/51				Upper Merrivale 2/32			
Oxide	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**
Na_2O	nd	2.5	0.6	2.2	0.2	1.8	0.4	1.6
MgO	1.5	1.8	1.5	1.8	2.7	2.4	2.8	2.6
Al_2O_3	7.1	13.4	9.7	13.1	5.3	14.9	4.4	15.7
SiO_2	4.5	38.1	19.1	38.6	14.3	39.0	10.7	39.4
P_2O_5	nd	0.4	0.2	0.6	nd	0.3	nd	0.5
K_2O	0.3	2.7	1.6	2.7	0.4	0.8	0.2	0.8
CaO	0.4	3.0	1.6	3.0	0.3	0.7	0.3	0.7
TiO_2	26.7	1.1	14.7	0.6	33.7	2.6	41.0	2.5
V_2O_5	0.5	0.0	0.4	0.0	0.8	nd	0.5	0.0
MnO	4.8	3.3	4.2	3.2	1.8	1.5	1.7	1.2
FeO	53.3	15.4	35.6	14.9	24.6	11.8	26.5	11.4
CuO	0.0	nd	nd	0.1	nd	nd	0.1	0.1
ZnO	nd	0.0	0.1	nd	0.0	0.0	nd	0.1
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.1	0.5	0.1	0.0	7.9	2.1	6.8	1.8
MoO_3	0.0	0.3	0.0	0.3	nd	0.4	nd	0.1
SnO	2.1	17.0	10.1	18.7	7.2	19.6	4.2	19.9
Sb_2O_3	nd	0.4	0.2	nd	nd	0.2	0.2	0.0
WO_3	nd	1.1	0.7	1.0	1.6	2.8	1.2	2.4
Sum	101.3	101	100.4	100.8	100.8	100.9	101.0	100.8

	Upper Merrivale 3/27*					Taw River 2/40	
Oxide	**Dendrite 1**	**Dark Matrix 1**	**Mid Crystal 1**	**Dendrite 2**	**Dark Matrix 2**	**Dendrite 1**	**Matrix 1**
Na_2O	0.2	0.1	nd	0.2	1.0	1.4	1.9
MgO	0.9	4.3	5.6	0.4	1.6	3.3	3.0
Al_2O_3	9.3	5.7	0.4	10.4	15.8	10.3	11.8
SiO_2	14.1	32.6	24.7	14.4	23.4	30.9	35.4
P_2O_5	0.1	0.3	0.3	nd	0.0	nd	nd
K_2O	1.1	1.4	nd	1.2	0.9	1.3	1.5
CaO	0.4	0.6	0.1	0.7	0.5	0.8	1.0
TiO_2	16.3	0.8	0.5	14.0	7.6	11.6	3.7
V_2O_5	0.7	0.1	0.1	0.4	0.3	0.3	0.0
MnO	2.1	3.0	4.3	2.2	2.1	1.8	1.2
FeO	48.3	42.8	65.1	43.6	40.3	14.1	9.6
CuO	0.0	0.0	0.1	0.0	0.0	0.0	nd
ZnO	0.0	nd	nd	0.1	0.0	0.1	nd
As_2O_3	nd	nd	0.0	nd	nd	nd	nd
ZrO_2	0.4	0.5	0.0	0.7	0.4	2.0	4.1
MoO_3	0.0	0.3	nd	0.2	0.2	0.3	0.8
SnO	5.3	6.6	0.1	8.9	5.6	17.0	20.1
Sb_2O_3	0.1	nd	0.0	0.3	nd	nd	0.1
WO_3	1.1	1.4	nd	2.8	1.3	5.7	7.4
Sum	100.4	100.5	101.3	100.5	101.0	100.9	101.6

* The matrix of the Upper Merrivale 3/27 slag appeared in places to contain both a pale dendritic phase and a mid-grey crystalline phase (Area 1), but elsewhere only the dendritic phase (Area 2).

	Thornworthy 2/45				Thornworthy 2/46				Trereife 4/21*	
Oxide	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**	**Dendrite 1**	**Matrix 1**	**Dendrite 2**	**Matrix 2**	**Dendrite 1**	**Matrix 1**
Na_2O	1.8	1.6	nd	3.0	nd	1.3	nd	0.9	nd	0.9
MgO	1.4	1.0	2.0	1.1	0.6	0.7	0.3	0.5	0.8	0.9
Al_2O_3	9.0	10.9	7.9	15.9	3.0	8.6	2.5	7.0	19.7	11.8
SiO_2	20.1	31.9	14.6	48.5	0.5	37.5	2.1	30.0	2.3	39.3
P_2O_5	0.2	0.3	0.0	0.4	0.0	0.0	nd	nd	nd	nd
K_2O	2.1	4.6	1.9	6.4	0.1	2.4	0.2	1.6	0.2	1.6
CaO	0.9	2.6	1.1	3.7	0.1	1.2	0.2	1.0	0.1	2.0
TiO_2	18.5	10.8	22.8	4.1	28.9	1.2	27.4	4.8	6.7	1.3
V_2O_5	0.5	0.3	0.3	0.0	0.4	0.1	0.6	0.1	0.5	nd
MnO	1.2	0.9	1.4	0.6	1.1	0.9	1.1	0.9	0.3	0.4
FeO	42.6	29.3	46.6	9.8	63.7	19.6	63.4	26.1	69.6	19.6
CuO	0.0	nd	nd	nd	0.0	0.0	nd	0.0	0.1	nd
ZnO	0.1	nd	nd	nd	0.0	nd	0.1	0.2	0.0	0.0
As_2O_3	nd	0.0	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.0	0.0	0.2	0.1	0.1	0.7	0.2	0.9	0.2	1.7
MoO_3	nd	nd	0.0	0.1	nd	0.1	nd	0.0	0.2	0.6
SnO	2.1	5.3	2.0	6.5	1.5	25.7	2.2	24.9	3.4	17.8
Sb_2O_3	nd	nd	0.1	nd	0.2	0.0	nd	0.0	nd	0.1
WO_3	0.4	0.8	nd	0.7	0.3	0.9	0.3	1.5	0.6	7.3
Sum	100.9	100.3	100.9	100.9	100.5	100.9	100.6	100.4	104.7	105.3

*Trereife 4/21 also contains crystal phases.

Figure A7.1: Graph showing differences in Al_2O_3 content between dendritic phases and slag matrix in slags from different sites

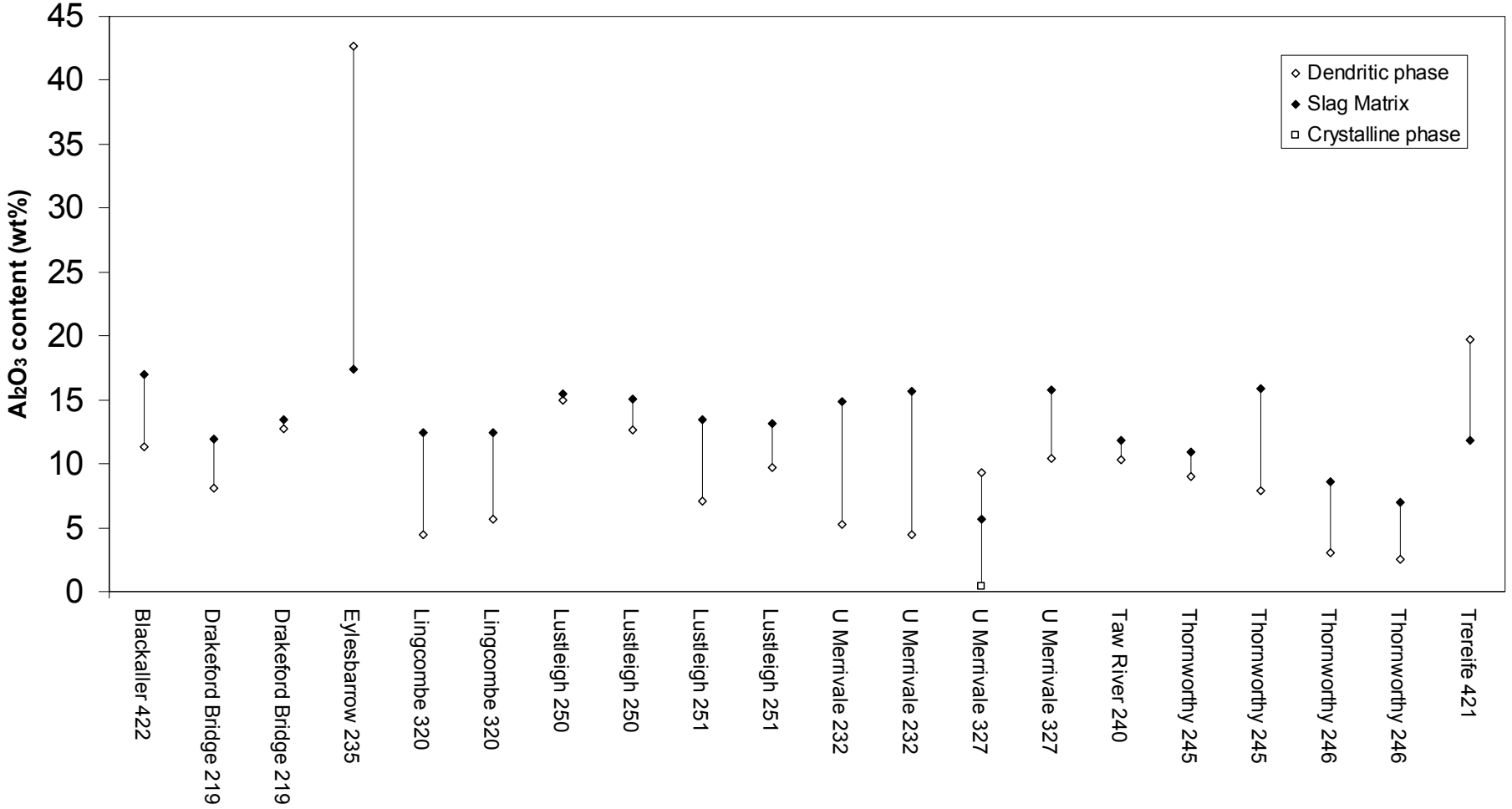


Figure A7.2: Graph showing differences in SiO_2 content between dendritic phases and slag matrix in slags from different sites

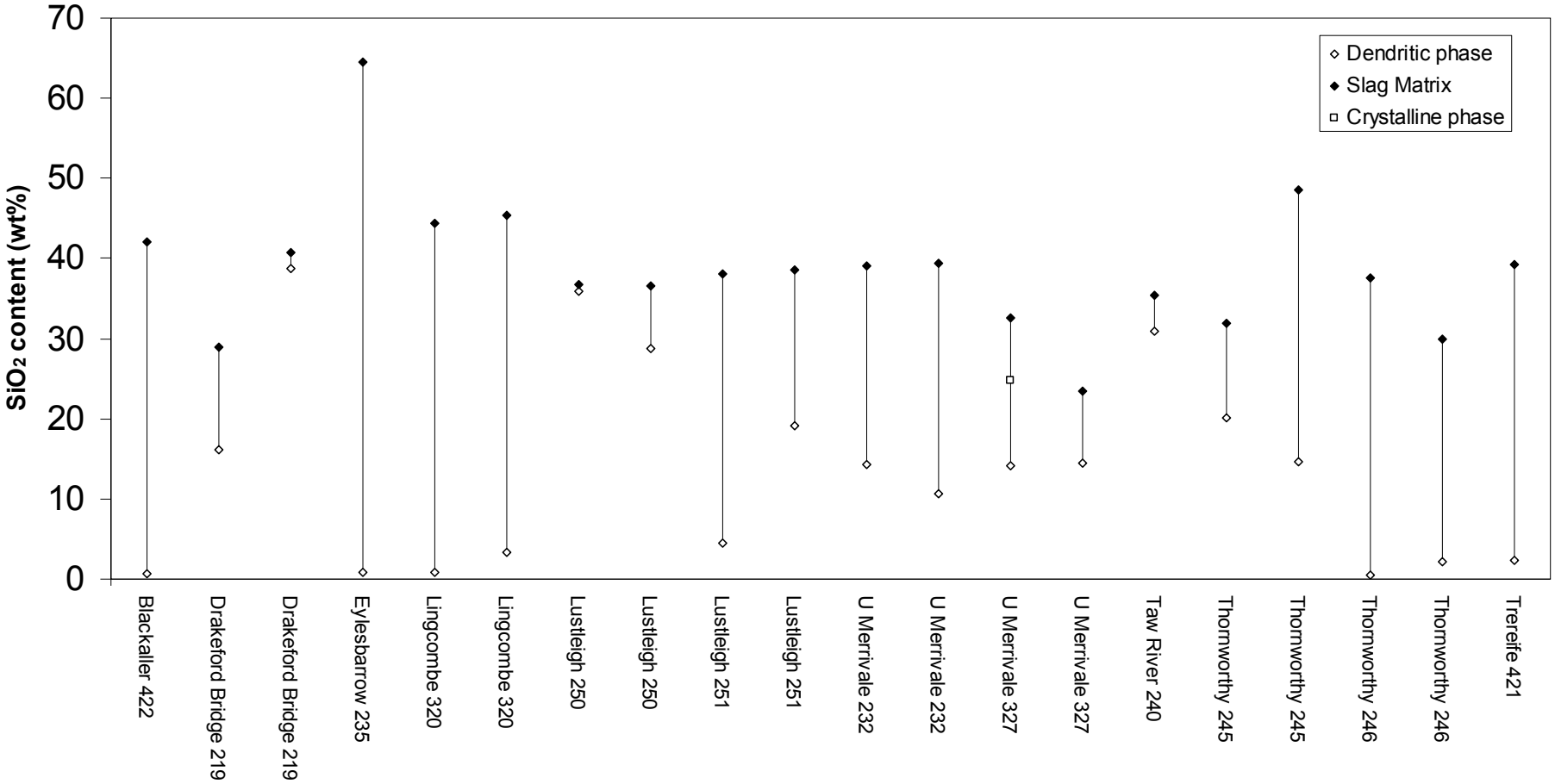


Figure A7.3: Graph showing differences in TiO_2 content between dendritic phases and slag matrix in slags from different sites

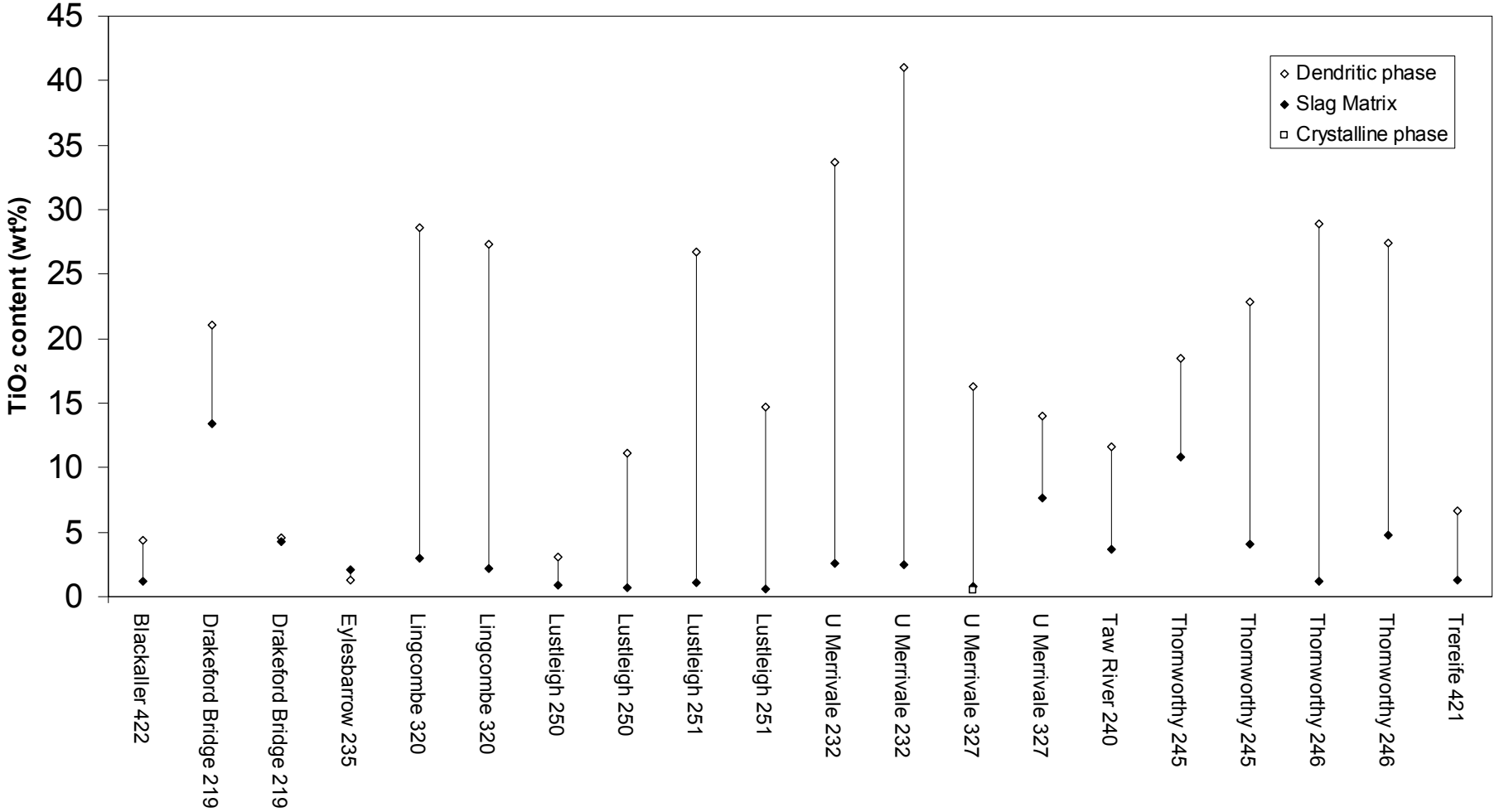


Figure A7.4: Graph showing differences in FeO content between dendritic phases and slag matrix in slags from different sites

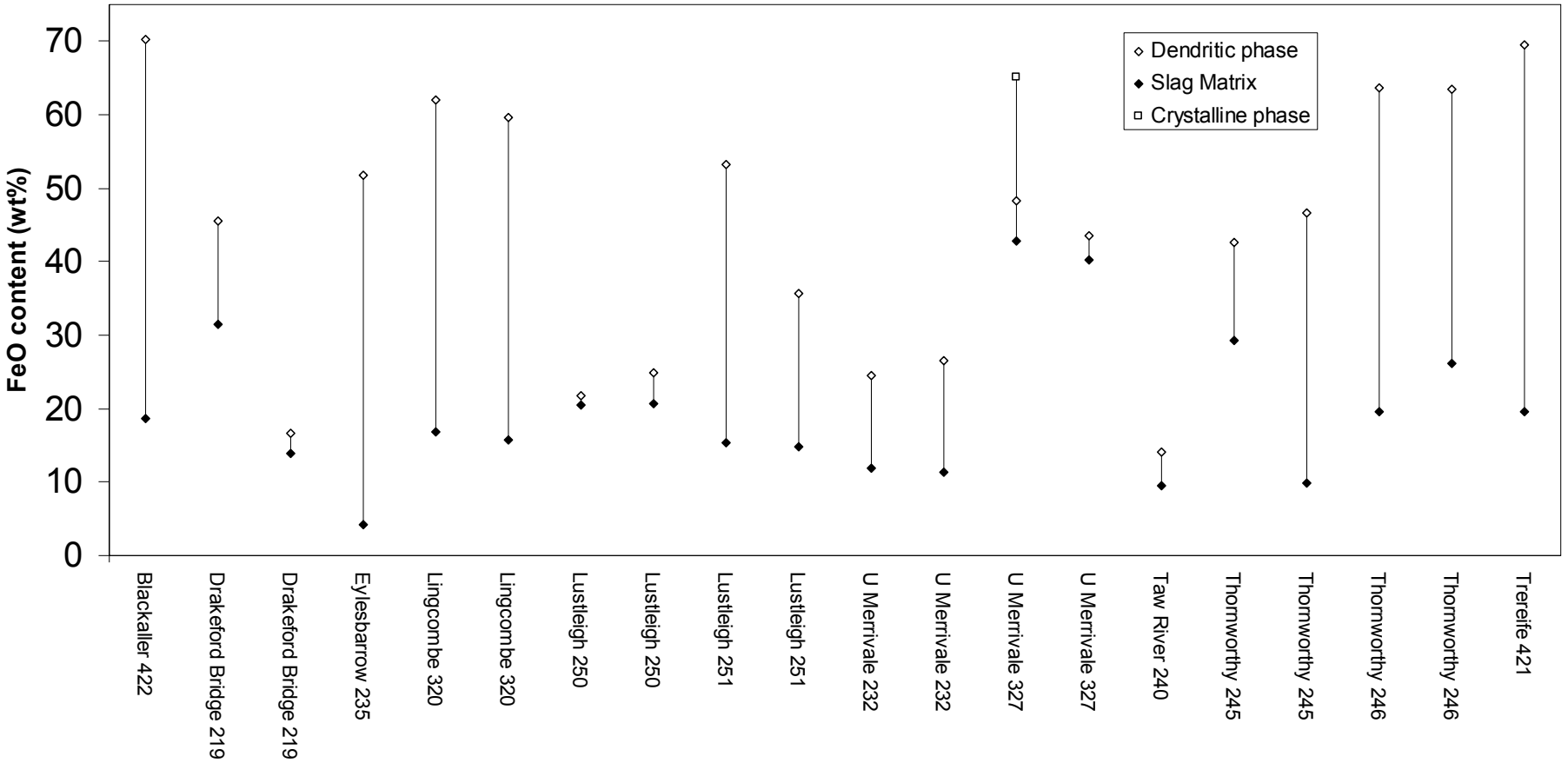


Figure A7.5: Graph showing differences in SnO content between dendritic phases and slag matrix in slags from different site

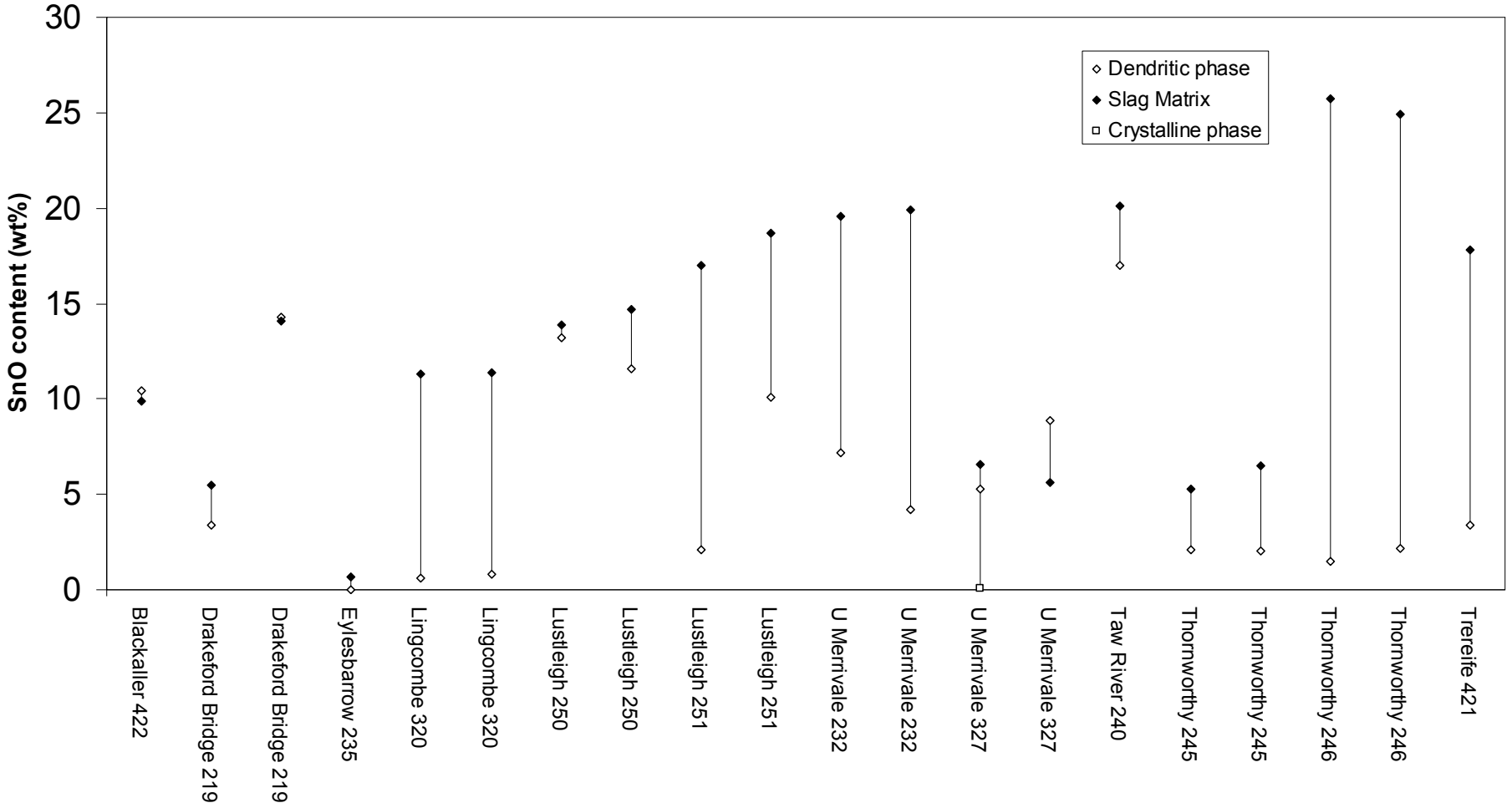
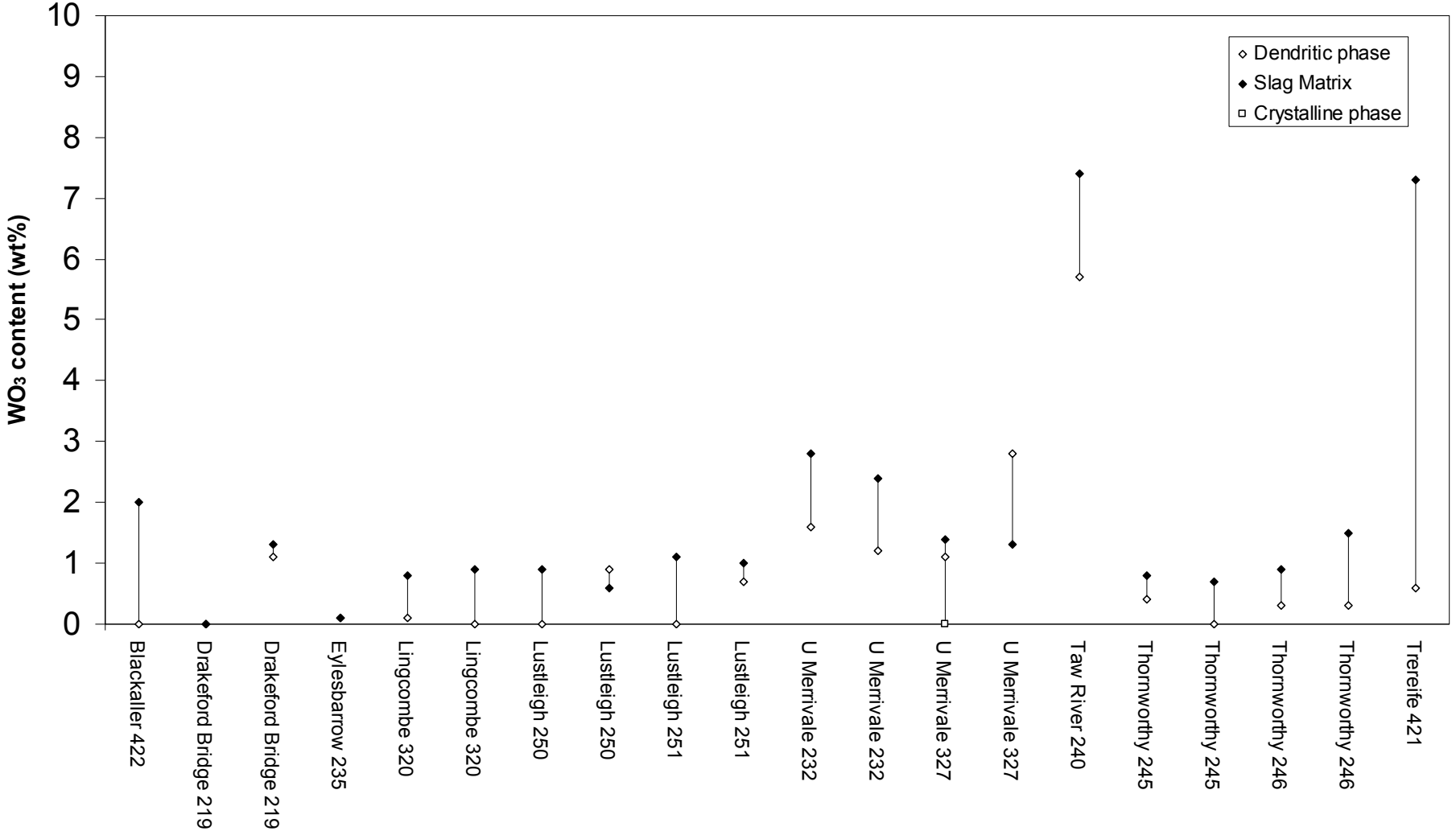


Figure A7.6: Graph showing differences in WO_3 content between dendritic phases and slag matrix in slags from different sites



Appendix 8: Chemical Composition of Crystalline Phases (wt%)

Analysis carried out using EDX-SEM. Major elements are highlighted. nd = not detected

	Carvedras 3/30						Charlestown 4/20*	
Oxide	**Light crystal 1**	**Mid crystal 1**	**Dark crystal 1**	**Light crystal 2**	**Mid crystal 2**	**Dark crystal 2**	**Light crystal 1**	**Dark matrix 1**
Na_2O	2.5	1.5	1.0	2.0	1.4	1.3	nd	1.2
MgO	1.2	nd	0.1	1.2	nd	0.1	0.7	1.0
Al_2O_3	18.6	75.7	22.4	18.5	63.9	51.2	18.0	12.1
SiO_2	56.8	23.6	52.0	54.9	32.8	42.5	3.7	40.1
P_2O_5	nd	0.0	nd	nd	0.0	nd	0.0	0.1
K_2O	2.6	0.1	4.4	2.5	0.4	0.9	0.3	1.9
CaO	1.7	0.1	1.7	1.6	0.2	0.3	0.1	1.0
TiO_2	2.4	0.9	2.9	2.3	1.2	1.3	15.2	1.0
V_2O_5	0.0	0.5	0.2	0.0	0.4	0.1	0.9	nd
MnO	0.4	0.0	0.2	0.4	nd	0.0	0.1	0.2
FeO	8.9	0.2	7.1	8.7	1.0	1.9	59.5	23.1
CuO	0.0	0.1	0.0	0.0	0.0	0.0	nd	nd
ZnO	0.0	0.0	0.0	nd	0.0	0.1	0.2	0.1
As_2O_3	nd	nd	0.0	nd	nd	nd	nd	nd
ZrO_2	0.0	nd	0.4	0.5	nd	nd	nd	0.8
MoO_3	0.0	nd	3.1	0.2	nd	0.1	nd	1.3
SnO	5.5	0.1	4.9	7.1	0.8	2.0	2.2	15.7
Sb_2O_3	0.1	0.0	0.0	0.4	nd	0.1	0.1	0.1
WO_3	0.2	0.3	0.3	0.8	0.3	0.0	0.2	1.6
Sum	100.9	103.1	100.7	101.1	102.4	101.9	101.2	101.3

* The matrix in Charlestown 4/20 contains some very small dendrites, so the figures quoted include both phases.

	Eylesbarrow 2/35				Eylesbarrow 4/05		Eylesbarrow 4/06	
Oxide	**Light crystal 1**	**Dark matrix 1**	**Light crystal 2**	**Dark matrix 2**	**Light crystal 1**	**Dark matrix 1**	**Light crystal 1**	**Dark matrix 1**
Na_2O	nd	2.9	0.1	2.3	1.6	1.3	1.5	1.9
MgO	4.9	0.8	4.3	0.7	1.2	0.2	0.8	0.5
Al_2O_3	39.1	20.2	38.9	16.7	13.2	45.2	15.6	21.4
SiO_2	1.3	62.1	1.2	49.3	74.6	47.8	60.8	57.3
P_2O_5	0.2	0.2	0.1	0.1	nd	nd	nd	0.4
K_2O	0.0	5.3	0.1	4.1	4.8	2.1	2.1	2.5
CaO	0.2	4.4	0.2	2.7	0.5	0.1	0.7	0.7
TiO_2	0.8	1.2	0.9	10.7	2.0	1.3	0.8	0.7
V_2O_5	0.1	nd	0.2	0.1	0.1	0.0	0.0	nd
MnO	0.1	0.1	0.4	0.0	0.1	0.0	0.0	0.0
FeO	54.2	3.7	54.6	12.5	3.9	4.1	8.9	4.5
CuO	nd	nd	nd	0.0	nd	nd	0.1	0.2
ZnO	nd	nd	0.1	nd	nd	nd	nd	0.2
As_2O_3	nd	nd	nd	nd	nd	nd	nd	nd
ZrO_2	nd	0.1	0.1	0.0	nd	nd	nd	nd
MoO_3	nd	0.3	0.0	0.0	0.1	0.1	0.1	1.2
SnO	0.2	0.2	0.2	1.6	nd	0.0	8.2	5.1
Sb_2O_3	0.2	0.1	nd	0.1	nd	nd	nd	0.2
WO_3	nd	nd	nd	0.1	nd	nd	0.0	0.1
Sum	101.3	101.6	101.4	101.0	102.1	102.2	99.6	96.9

	Upper Merrivale 2/27							
Oxide	**Mid crystal 1**	**Dark crystal 1**	**Light crystal 1**	**Mid crystal 2**	**Dark crystal 2**	**Light crystal 2**	**Mid crystal 3**	**Dark crystal 3**
Na_2O	2.4	nd	nd	1.5	nd	nd	1.4	nd
MgO	nd	4.9	nd	nd	5.0	nd	0.0	4.1
Al_2O_3	8.2	0.0	0.2	7.2	0.1	0.4	6.5	0.2
SiO_2	27.4	30.7	18.7	25.3	31.0	18.7	25.3	31.1
P_2O_5	nd	nd	nd	nd	nd	nd	nd	0.0
K_2O	2.3	0.0	nd	1.5	nd	0.0	1.2	0.0
CaO	0.7	0.1	0.1	0.8	0.0	0.1	0.8	0.1
TiO_2	0.3	0.2	0.1	0.7	0.1	0.4	0.6	0.0
V_2O_5	0.1	0.0	0.1	nd	0.0	0.1	0.2	0.0
MnO	0.4	3.3	1.5	0.6	3.3	1.4	0.7	3.5
FeO	9.2	61.7	16.7	13.1	61.4	16.7	14.4	63.0
CuO	0.1	0.0	nd	0.0	0.0	0.0	nd	0.0
ZnO	0.0	0.1	nd	0.1	0.2	nd	nd	nd
As_2O_3	nd	0.0	1.6	nd	nd	1.4	nd	nd
ZrO_2	1.5	0.1	8.9	1.1	0.0	8.6	0.9	nd
MoO_3	0.8	0.0	5.5	0.8	0.0	5.2	0.5	0.0
SnO	42.0	nd	0.1	42.7	nd	0.5	43.7	0.1
Sb_2O_3	0.2	nd	0.1	0.2	nd	0.1	0.0	nd
WO_3	5.8	0.3	61.8	4.8	0.4	60.5	4.3	nd
Sum	101.4	101.4	115.4	100.4	101.5	114.1	100.5	102.1

	Trereife / Stable Hobba 3/35									
Oxide	**Large pale crystal 1**	**Small crystal 1**	**Large dark crystal 1**	**Large mid crystal 1**	**Light crystal 1**	**Large pale crystal 2**	**Small crystal 2**	**Large dark crystal 2**	**Large mid crystal 2**	**Light crystal 2**
Na_2O	nd	nd	1.8	1.2	1.8	nd	1.6	nd	1.3	1.8
MgO	nd	nd	2.4	nd	0.2	nd	0.0	1.4	0.0	0.1
Al_2O_3	0.2	3.6	1.8	12.2	12.2	0.3	12.5	0.1	11.5	11.4
SiO_2	18.0	21.9	30.6	37.3	38.7	18.1	38.8	27.9	37.2	39.8
P_2O_5	nd	nd	nd	nd	nd	nd	nd	0.8	nd	nd
K_2O	0.0	0.5	0.2	1.8	2.9	0.0	2.1	0.0	2.0	2.2
CaO	0.1	0.9	0.5	3.3	3.2	0.1	3.1	0.1	3.2	2.2
TiO_2	nd	0.3	0.2	1.0	0.8	0.1	0.6	0.2	0.8	0.7
V_2O_5	0.1	0.1	0.0	nd	0.0	0.1	nd	0.0	nd	nd
MnO	0.4	0.4	1.2	0.3	0.1	0.5	0.3	1.0	0.1	0.2
FeO	17.3	16.5	59.5	10.9	10.5	17.5	15.3	69.3	9.4	18.0
CuO	nd	0.0	nd	0.0	0.0	0.0	nd	nd	nd	0.0
ZnO	nd	nd	nd	0.0	nd	nd	nd	0.1	nd	0.0
As_2O_3	1.6	0.7	nd	0.0	nd	1.3	nd	0.2	nd	nd
ZrO_2	8.0	5.0	0.6	1.7	1.0	7.9	0.9	nd	0.9	0.6
MoO_3	5.1	3.5	0.1	1.6	2.5	5.2	1.2	nd	1.1	2.4
SnO	nd	7.2	1.8	26.5	24.4	0.0	21.2	0.2	27.8	17.6
Sb_2O_3	0.0	0.0	nd	nd	nd	nd	nd	nd	nd	0.4
WO_3	63.8	46.8	0.8	3.6	3.4	63.1	4.0	nd	6.7	3.3
Sum	114.6	107.4	101.5	101.4	101.7	114.2	101.6	101.3	102.0	100.7

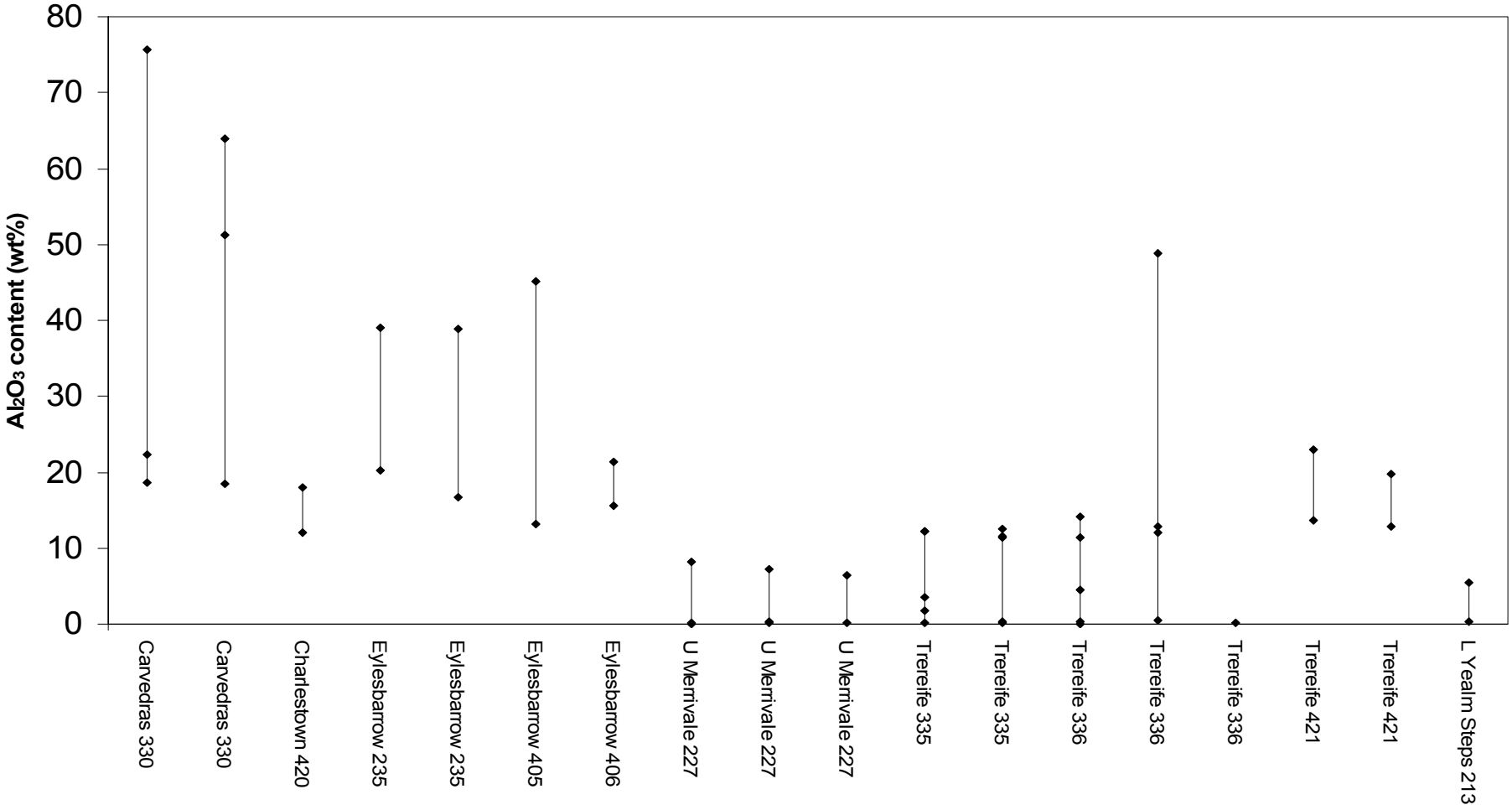
	Trereife / Stable Hobba 3/36									
Oxide	**Large regular crystal 1**	**Small crystal 1**	**Large dark crystal 1**	**Large mid crystal 1**	**Light crystal 1**	**Large regular crystal 2**	**Large mid crystal 2**	**Large dark crystal 2**	**Light crystal 2**	**Large regular crystal 3**
Na_2O	nd	nd	nd	1.1	1.6	nd	1.0	nd	1.6	nd
MgO	nd	0.6	1.2	nd	0.1	nd	nd	1.3	0.1	nd
Al_2O_3	0.3	4.5	0.0	11.4	14.1	0.5	12.0	48.9	12.8	0.2
SiO_2	16.7	31.5	26.9	34.4	41.4	19.0	41.7	4.2	39.3	16.7
P_2O_5	nd	0.0	nd	nd	nd	nd	0.0	0.0	nd	nd
K_2O	0.0	1.3	0.0	1.9	2.6	0.0	3.1	0.4	2.9	0.1
CaO	0.1	1.5	0.1	3.1	3.6	0.2	3.1	0.3	3.8	0.2
TiO_2	0.0	0.5	0.1	1.1	1.2	0.2	0.7	1.3	1.1	0.2
V_2O_5	0.0	nd	0.0	nd	nd	0.0	nd	0.7	nd	nd
MnO	0.4	0.6	1.2	0.1	0.2	0.7	0.0	0.3	0.2	0.6
FeO	17.7	46.6	72.1	12.3	13.7	29.8	11.0	41.5	13.9	18.4
CuO	nd	nd	0.0	nd	0.0	nd	0.0	nd	0.1	nd
ZnO	nd	nd	0.0	nd	0.0	nd	0.1	0.2	0.0	nd
As_2O_3	1.4	nd	nd	nd	nd	1.0	nd	nd	nd	1.3
ZrO_2	7.6	0.5	0.3	1.3	0.8	5.7	0.6	0.3	1.0	7.5
MoO_3	4.5	0.9	0.1	1.5	1.3	3.7	0.8	0.1	2.6	4.5
SnO	0.1	9.4	0.0	24.7	16.1	0.6	22.8	1.4	17.1	0.1
Sb_2O_3	0.1	0.2	nd	0.2	0.3	0.0	0.2	nd	0.2	0.0
WO_3	63.9	2.8	nd	5.7	4.7	48.4	3.4	0.3	4.4	63.1
Sum	112.8	100.9	102.0	98.8	101.7	109.8	100.5	101.2	101.1	112.9

	Trereife / Stable Hobba 4/21*			
Oxide	**Light crystal 1**	**Dark crystal 1**	**Light crystal 2**	**Dark crystal 2**
Na_2O	nd	1.0	nd	0.8
MgO	1.0	1.0	0.9	0.9
Al_2O_3	22.9	13.7	19.8	12.9
SiO_2	0.5	36.6	0.4	35.9
P_2O_5	nd	nd	nd	nd
K_2O	0.1	1.7	nd	1.7
CaO	0.0	2.0	0.0	1.9
TiO_2	5.3	2.5	4.2	2.4
V_2O_5	0.5	nd	0.4	nd
MnO	0.4	0.5	0.4	0.4
FeO	68.4	21.5	71.7	19.0
CuO	0.0	nd	nd	0.0
ZnO	0.1	nd	0.2	0.1
As_2O_3	nd	nd	nd	nd
ZrO_2	0.2	1.4	0.2	1.2
MoO_3	nd	0.3	0.0	0.6
SnO	2.0	16.7	2.4	16.0
Sb_2O_3	0.2	0.1	0.0	0.7
WO_3	nd	6.8	0.5	6.3
Sum	101.6	105.8	101.1	100.8

*Trereife 4/21 also contains dendrites.

	Lower Yealm Steps 2/13			
Oxide	**Mid crystal 1**	**Dark crystal 1**	**Mid crystal 2**	**Dark crystal 2**
Na_2O	1.0	nd	0.9	nd
MgO	nd	0.2	0.1	3.2
Al_2O_3	5.4	0.3	5.8	0.5
SiO_2	20.5	28.6	19.0	28.5
P_2O_5	0.1	nd	0.0	0.1
K_2O	1.0	0.0	1.0	0.1
CaO	0.9	0.2	1.0	0.1
TiO_2	0.0	0.1	0.3	0.1
V_2O_5	0.0	0.1	0.1	0.0
MnO	0.0	0.5	0.0	0.5
FeO	10.0	70.5	9.0	67.5
CuO	0.0	0.1	0.0	nd
ZnO	nd	0.0	0.0	0.1
As_2O_3	0.0	0.0	nd	nd
ZrO_2	0.4	0.1	0.5	0.1
MoO_3	0.2	0.0	0.1	0.0
SnO	59.0	1.1	61.1	0.7
Sb_2O_3	0.3	0.1	0.6	0.0
WO_3	1.3	nd	0.9	nd
Sum	100.1	101.9	100.4	101.5

Figure A8.1: Graph showing differences in Al_2O_3 content between crystalline phases in slags from different sites



Note: Owing to the varied nature of the crystalline phases in these samples no attempt has been made to distinguish between types in these plots.

Figure A8.2: Graph showing differences in SiO_2 content between crystalline phases in slags from different sites

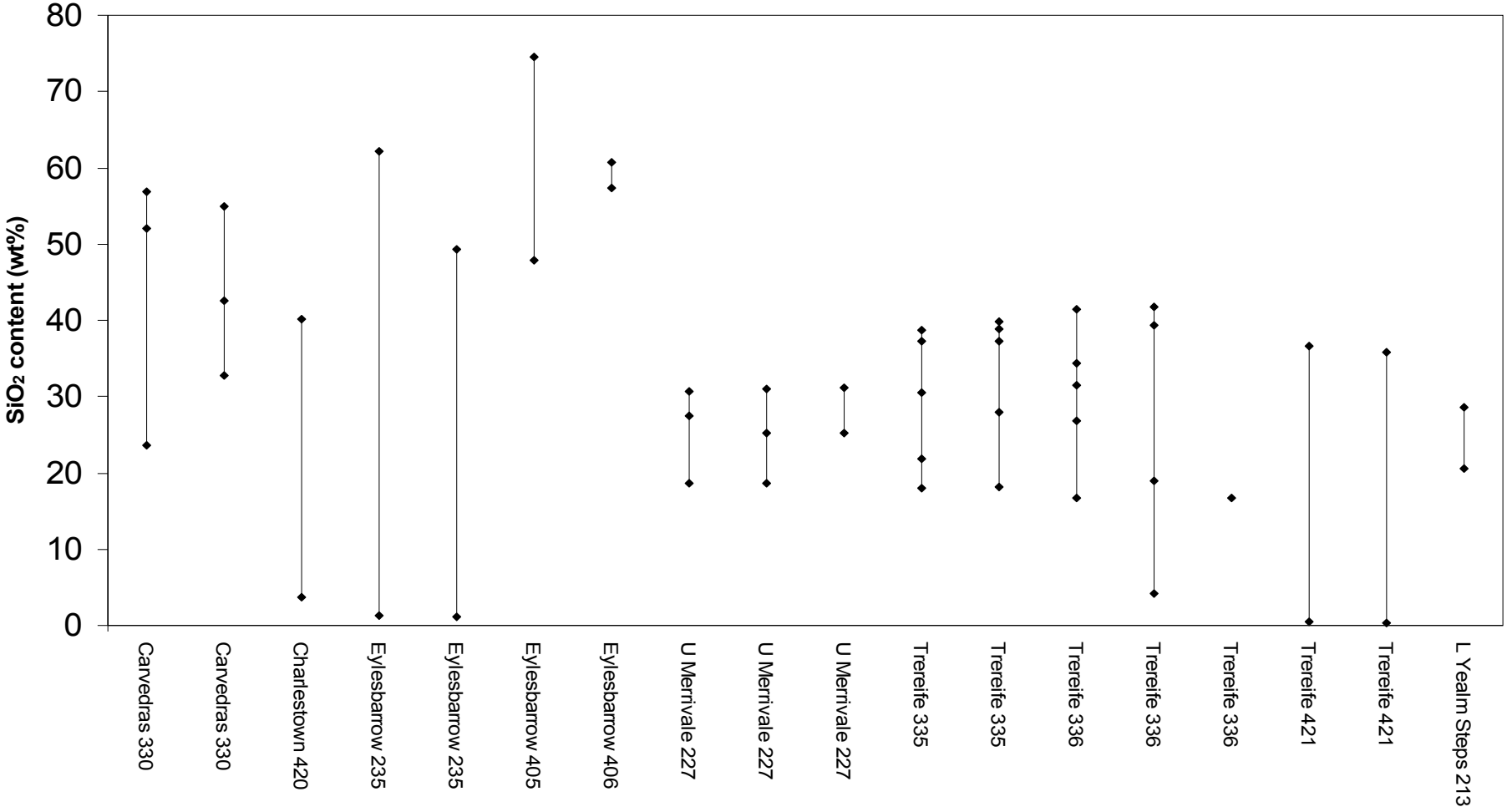


Figure A8.3: Graph showing differences in TiO_2 content between crystalline phases in slags from different sites

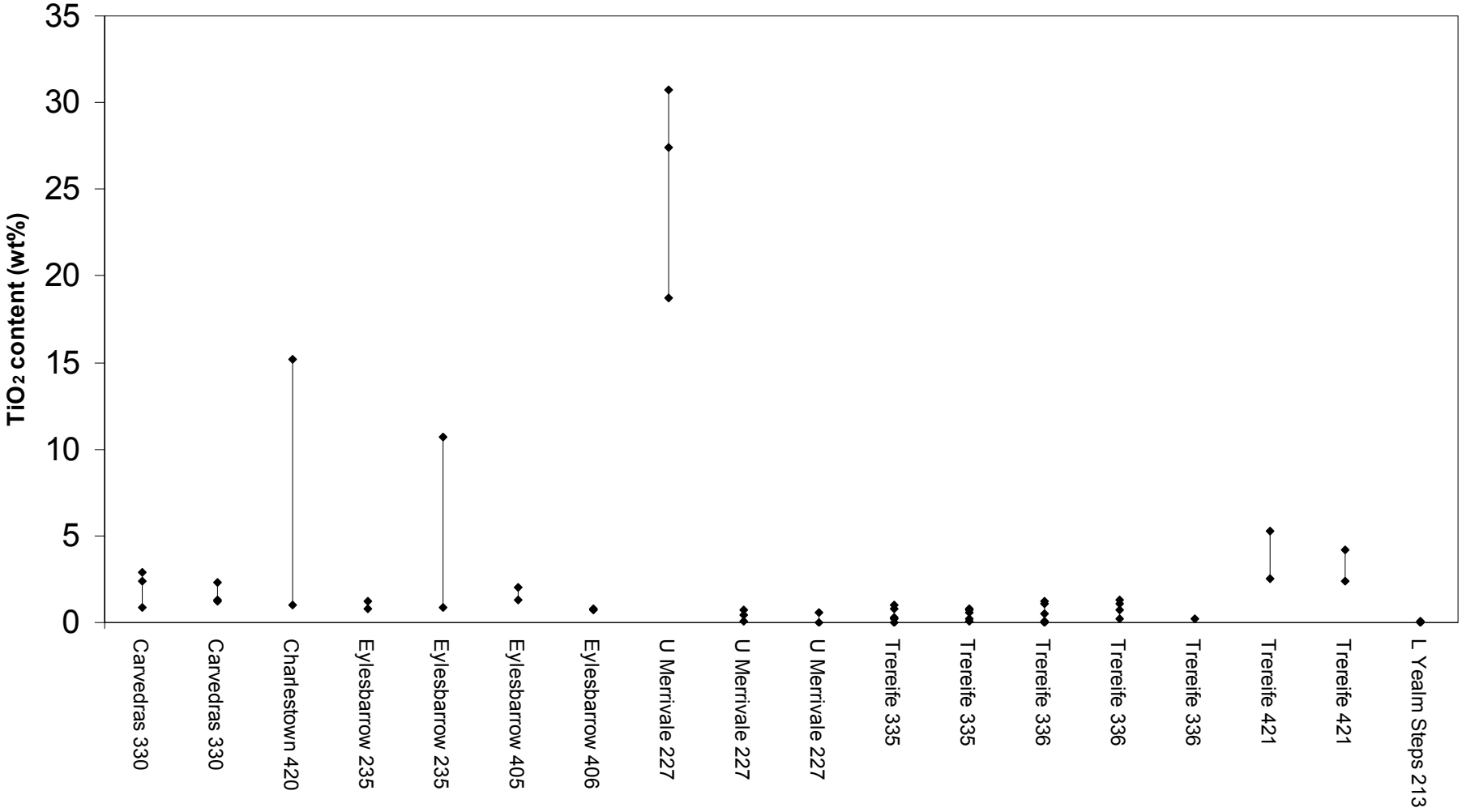


Figure A8.4: Graph showing differences in FeO content between crystalline phases in slags from different sites

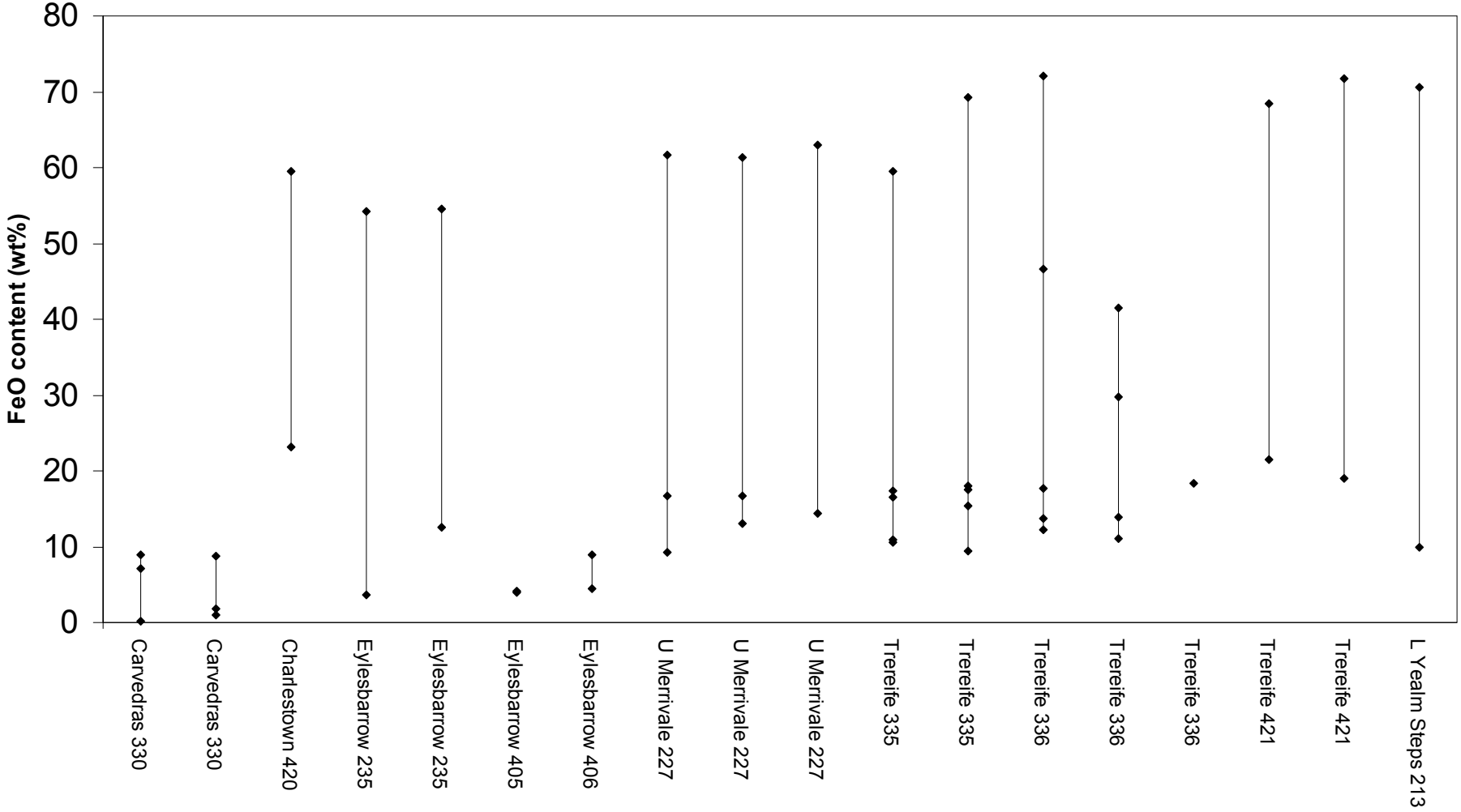


Figure A8.5: Graph showing differences in SnO content between crystalline phases in slags from different sites

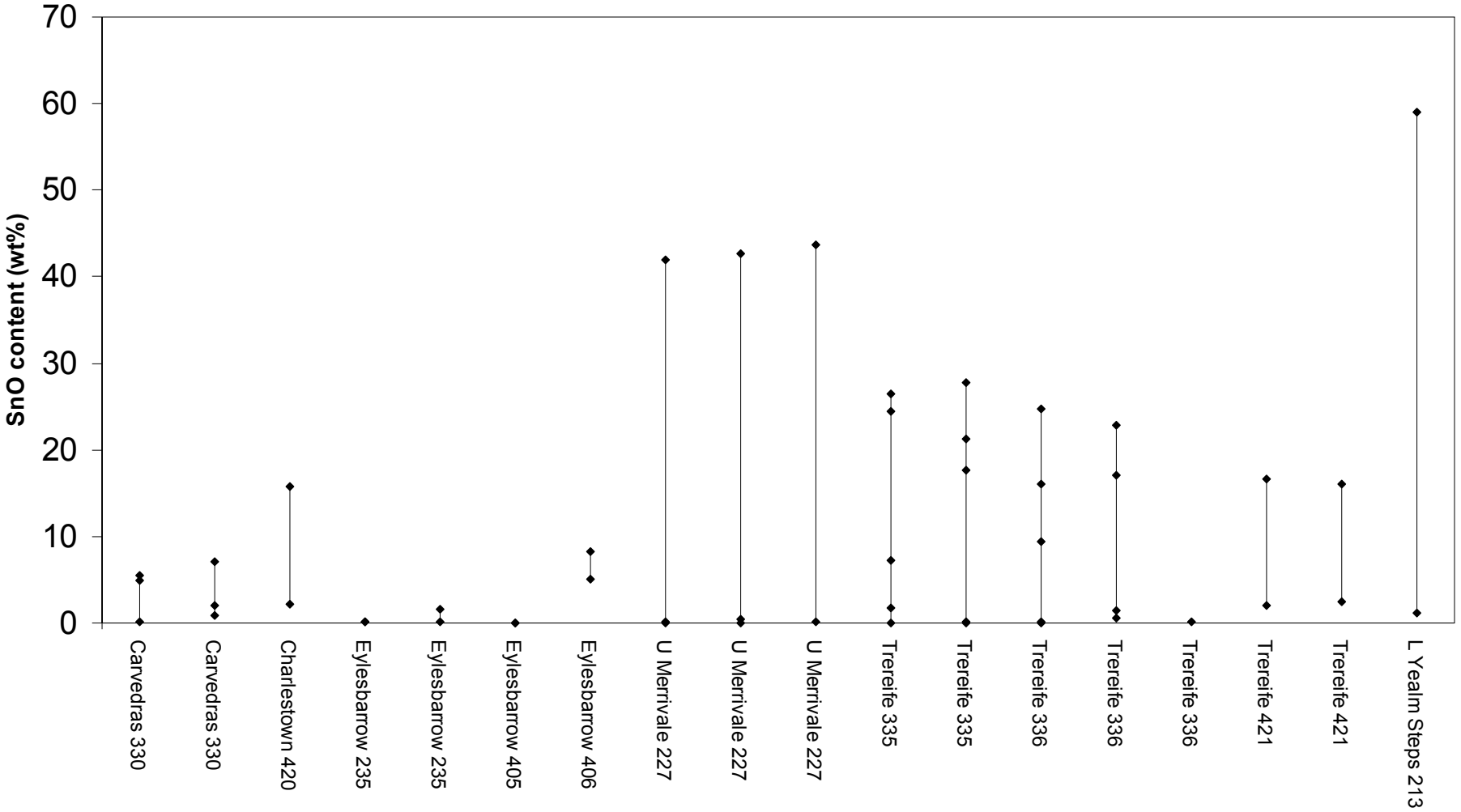
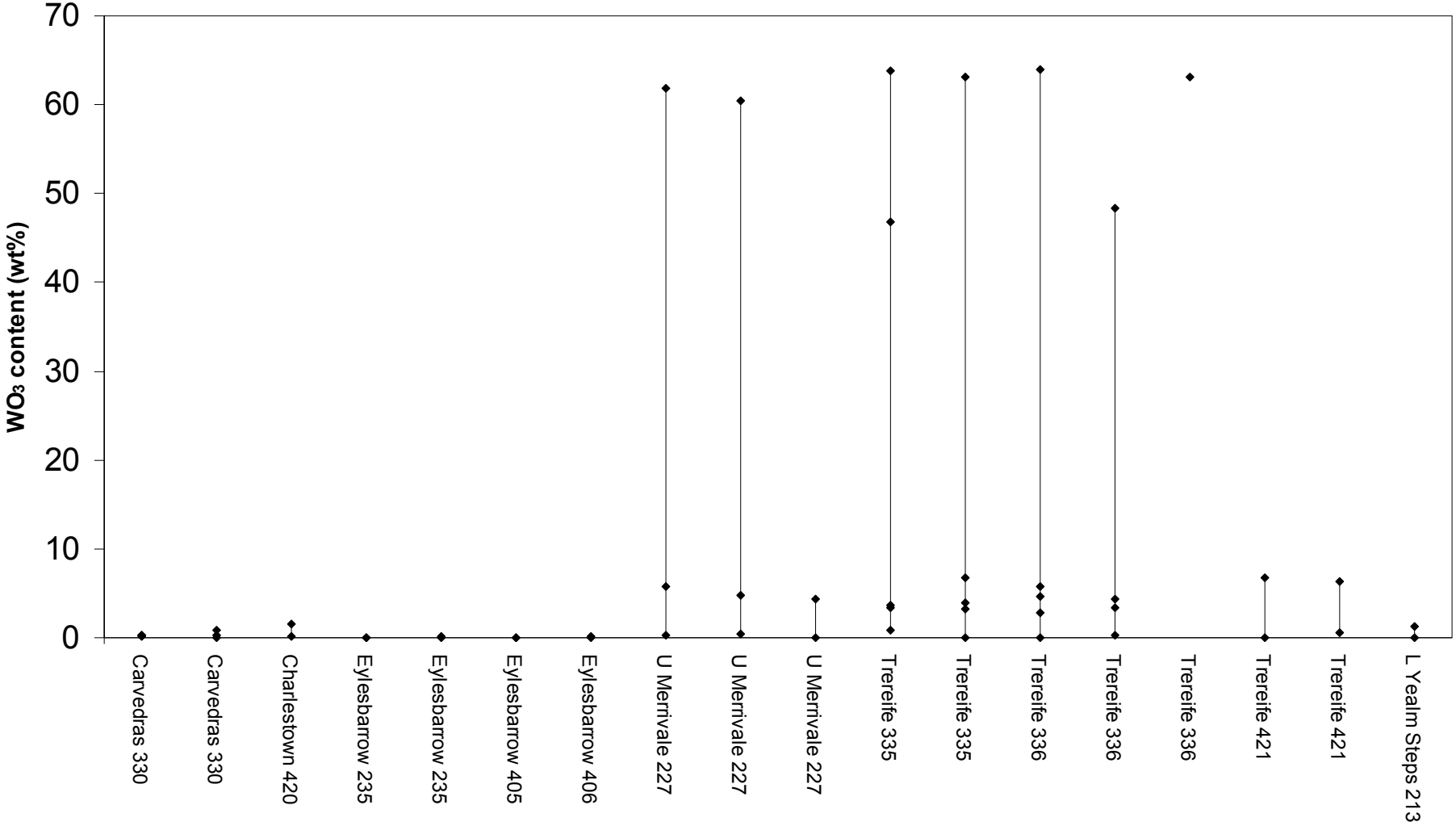


Figure A8.6: Graph showing differences in WO_3 content between crystalline phases in slags from different sites



Appendix 9: Chemical Composition of Isolated Crystals in Non-crystalline Slags (wt%)

Analysis carried out using EDX-SEM. Elements with higher concentrations are shaded. nd = not detected

	Taw River 2/15		Caerloggas 3/44				
Oxide	**Pale spot 1**	**Pale spot 2**	**Dark Crystal 1 in Crystal cluster**	**Dark Needle 1 in Crystal cluster**	**Centre of Crystal cluster**	**Dark Crystal 2 in Crystal cluster**	**Dark Needle 2 in Crystal cluster**
Na_2O	0.6	0.7	1.4	1.6	2.9	1.3	1.4
MgO	1.9	0.8	7.3	1.0	nd	3.8	0.6
Al_2O_3	5.3	2.0	30.1	39.9	47.2	17.7	59.3
SiO_2	11.6	5.9	15.3	17.0	38.2	17.2	8.6
P_2O_5	nd	0.0	nd	0.0	nd	nd	0.0
K_2O	0.4	0.4	0.7	0.6	5.5	0.9	0.5
CaO	0.4	0.2	0.5	0.5	0.3	0.9	0.3
TiO_2	18.6	17.7	1.0	0.9	0.2	1.3	0.9
V_2O_5	0.4	0.4	0.1	0.1	0.0	0.2	0.0
MnO	1.5	0.4	0.5	0.4	0.1	0.5	0.1
FeO	13.6	3.2	7.5	3.0	0.3	5.6	1.9
CuO	0.0	nd	nd	0.0	0.1	0.2	0.1
ZnO	0.2	0.0	0.1	nd	0.2	0.2	0.2
As_2O_3	nd	nd	nd	nd	nd	nd	nd
ZrO_2	24.9	49.9	0.2	0.3	0.1	0.4	0.1
MoO_3	0.0	nd	0.0	0.1	nd	0.1	0.0
SnO	16.5	11.9	34.1	32.5	6.9	47.4	23.3
Sb_2O_3	0.1	0.2	0.4	0.9	nd	0.4	0.3
WO_3	4.8	3.2	2.5	2.0	0.6	3.0	1.2
Sum	100.8	97.1	101.7	100.8	102.5	101.0	98.7

	Caerloggas 3/45						
Oxide	**Dark Crystal 1 in Crystal cluster**	**Dark Needle 1 in Crystal cluster**	**Centre of Crystal cluster**	**Dark Crystal 2 in Crystal cluster**	**Dark Needle 2 in Crystal cluster**	**Pale crystal 1**	**Pale crystal 2**
Na_2O	0.5	1.2	0.6	1.6	1.1	0.3	0.2
MgO	17.9	1.6	nd	5.2	nd	nd	0.0
Al_2O_3	65.8	34.7	71.9	23.4	83.0	0.3	0.5
SiO_2	0.8	24.8	21.4	21.0	7.6	0.6	1.0
P_2O_5	0.1	nd	nd	0.0	0.0	nd	nd
K_2O	0.0	0.5	0.1	0.6	0.1	nd	nd
CaO	0.0	0.6	0.1	0.4	0.2	0.9	0.4
TiO_2	0.1	1.3	0.3	1.7	0.6	0.8	1.7
V_2O_5	0.4	0.0	0.1	0.2	0.2	0.0	0.1
MnO	0.6	0.4	0.1	0.6	0.1	0.0	0.0
FeO	16.1	4.4	0.9	8.0	1.0	0.2	0.4
CuO	nd	nd	0.0	0.0	nd	nd	0.1
ZnO	0.1	0.0	nd	0.0	0.0	nd	nd
As_2O_3	nd	nd	nd	nd	nd	nd	nd
ZrO_2	0.1	0.4	0.1	0.4	0.2	0.1	0.4
MoO_3	0.1	0.2	0.3	0.2	0.2	nd	nd
SnO	0.3	32.4	6.4	34.4	7.8	93.6	95.2
Sb_2O_3	nd	0.0	nd	nd	0.1	0.2	0.4
WO_3	0.1	2.6	nd	3.3	0.0	nd	1.8
Sum	103.0	105.1	102.4	101.1	102.3	96.9	102.2

	Crift Farm 4/17				Week Ford 4/23	
Oxide	**Dark Needle 1 in Crystal cluster**	**Dark Crystal 1 in Crystal cluster**	**Dark Needle 2 in Crystal cluster**	**Dark Crystal 2 in Crystal cluster**	**Pale crystal 1**	**Pale crystal 2**
Na_2O	0.4	2.3	1.4	1.3	1.1	2.4
MgO	0.4	3.1	nd	nd	0.5	3.4
Al_2O_3	73.6	21.6	99.0	75.3	nd	14.0
SiO_2	17.6	40.8	1.8	20.2	31.0	39.8
P_2O_5	nd	nd	0.2	0.2	1.4	nd
K_2O	0.3	1.4	0.0	0.0	nd	1.2
CaO	0.2	0.9	0.1	0.0	nd	0.4
TiO_2	0.8	2.4	0.3	2.4	0.1	6.6
V_2O_5	0.1	0.0	0.0	0.2	0.0	0.4
MnO	0.1	0.3	0.0	0.0	0.0	0.2
FeO	2.1	5.7	0.3	0.0	0.2	9.5
CuO	nd	0.0	nd	0.1	nd	nd
ZnO	nd	nd	nd	0.1	0.0	0.3
As_2O_3	nd	nd	nd	nd	nd	nd
ZrO_2	0.1	0.1	nd	nd	71.8	19.9
MoO_3	0.1	nd	0.1	0.0	nd	nd
SnO	5.7	16.8	0.6	0.1	0.0	4.1
Sb_2O_3	nd	nd	0.0	0.0	nd	nd
WO_3	0.3	2.0	0.0	0.4	0.0	0.3
Sum	101.7	97.2	103.6	100.3	106.1	102.5

Appendix 10: Composition of Ore Samples determined by ICPMS pnq = present, not quantifiable X = detector swamped

Run	Label	7Li ppm	9Be ppm	11B ppm	23Na ppm	24Mg ppm	27Al ppm	29Si ppm	31P ppm	33S ppm	39K ppm	44Ca ppm	45Sc ppm
1a	Caerloggas 4/12	45	1	357	561	17	1135	568	2	pnq	121	21	39
1b	Caerloggas 4/12	37	1	279	564	21	1030	475	4	pnq	146	25	48
1c	Caerloggas 4/12	31	1	267	561	23	1078	479	5	pnq	140	26	53
	Mean of Caerloggas 4/12	37	1	301	562	20	1081	507	4	pnq	136	24	47
1a	Caerloggas 4/13	0	2	0	pnq	0	213	pnq	0	pnq	30	pnq	0
1b	Caerloggas 4/13	0	1	0	pnq	0	223	pnq	0	pnq	38	pnq	0
1c	Caerloggas 4/13	0	1	0	pnq	0	235	pnq	0	pnq	43	pnq	0
	Mean of Caerloggas 4/13	0	1	0	pnq	0	223	pnq	0	pnq	37	pnq	0
1a	Chysauster 4/30	2	0	156	5	49	194	3167	0	pnq	34	0	0
1b	Chysauster 4/30	1	0	257	pnq	63	295	953	45	pnq	24	13	0
1c	Chysauster 4/30	5	1	967	450	399	1906	6942	52	pnq	83	121	0
	Mean of Chysauster 4/30	3	1	460	151	170	799	3688	32	pnq	47	44	0
1a	Crift Farm 4/11	6	1	2703	3350	502	8625	4553	85	pnq	929	141	0
1b	Crift Farm 4/11	13	2	2763	3641	704	9451	5104	118	pnq	1102	217	0
1c	Crift Farm 4/11	7	1	2061	3303	541	7062	3813	114	pnq	1052	192	0
	Mean of Crift Farm 4/11	9	1	2509	3431	582	8379	4490	105	pnq	1028	183	0
2a	Crift Farm 4/11	3	1	1549	2773	283	5872	3026	49	pnq	889	42	0
2b	Crift Farm 4/11	5	1	1764	2894	405	6318	3784	52	pnq	877	56	0
2c	Crift Farm 4/11	5	1	1000	2703	265	5545	2277	71	pnq	939	44	0
	Mean of Crift Farm 4/11	4	1	1438	2790	318	5912	3029	57	pnq	902	47	0
1a	Dean Moor 3/48	114	31	7526	15050	6293	41120	52600	411	2103	19470	880	15
1b	Dean Moor 3/48	17	31	121	13570	1003	18130	37140	498	1542	15130	268	4
1c	Dean Moor 3/48	19	28	303	5040	1172	12000	22130	478	1022	10350	408	4
	Mean of Dean Moor 3/48	50	30	2650	11220	2823	23750	37290	462	1556	14980	519	8
2a	Dean Moor 3/48	79	25	3251	5014	2473	10130	7575	204	137	1205	776	5
2b	Dean Moor 3/48	21	17	428	3603	434	2476	9516	128	pnq	1090	356	3
2c	Dean Moor 3/48	36	16	424	9662	1645	11830	18600	466	80	4305	673	3
	Mean of Dean Moor 3/48	45	19	1368	6093	1517	8147	11900	266	15	2200	602	4

Run	Label	7Li ppm	9Be ppm	11B ppm	23Na ppm	24Mg ppm	27Al ppm	29Si ppm	31P ppm	33S ppm	39K ppm	44Ca ppm	45Sc ppm
3a	Dean Moor 3/48	10	13	309	2597	186	2298	8454	130	pnq	1344	382	6
3b	Dean Moor 3/48	33	9	1714	3304	653	5688	9781	166	pnq	1470	496	4
3c	Dean Moor 3/48	20	19	330	3056	233	2611	2749	195	pnq	1602	590	3
	Mean of Dean Moor 3/48	21	14	785	2986	357	3532	6995	164	pnq	1472	489	4
4a	Dean Moor 3/48	26	13	843	3986	751	6096	4463	243	pnq	2176	700	1
4b	Dean Moor 3/48	6	17	71	2736	228	2485	2129	170	pnq	1861	477	1
4c	Dean Moor 3/48	13	19	503	2919	437	3591	1777	146	pnq	1485	580	1
	Mean of Dean Moor 3/48	15	16	473	3214	472	4058	2790	187	pnq	1841	586	1
1a	Upper Merrivale 4/10	7	1	647	78	345	986	2748	0	pnq	31	62	0
1b	Upper Merrivale 4/10	6	1	509	31	269	844	2612	0	pnq	31	51	0
1c	Upper Merrivale 4/10	2	1	301	pnq	119	401	1616	0	pnq	28	pnq	0
	Mean of Upper Merrivale 4/10	5	1	486	36	244	744	2325	0	pnq	30	38	0
2a	Upper Merrivale 4/10	2	0	153	pnq	54	159	449	0	pnq	18	pnq	0
2b	Upper Merrivale 4/10	3	0	228	pnq	98	338	549	0	pnq	29	pnq	0
2c	Upper Merrivale 4/10	27	2	1380	808	1098	3460	7090	0	pnq	80	418	2
	Mean of Upper Merrivale 4/10	11	1	587	808	417	1319	2696	0	pnq	42	418	0
1a	Metherel 4/14	18	0	6036	4473	3385	19320	8555	64	pnq	807	266	1
1b	Metherel 4/14	25	0	5619	4552	3532	20960	9733	157	pnq	1206	333	1
1c	Metherel 4/14	33	1	5736	4992	4166	24270	11960	254	pnq	1635	409	2
	Mean of Metherel 4/14	26	1	5797	4672	3694	21510	10080	159	pnq	1216	336	1
2a	Metherel 4/14	19	0	5677	4972	3157	19960	8565	66	pnq	1008	254	3
2b	Metherel 4/14	18	0	5688	4987	3156	19840	8516	61	pnq	1048	260	3
2c	Metherel 4/14	17	0	5696	4916	3147	19760	8396	56	pnq	983	258	3
	Mean of Metherel 4/14	18	0	5687	4958	3153	19850	8492	61	pnq	1013	257	3

Run	Label	47Ti ppm	51V ppm	52Cr ppm	55Mn ppm	56Fe ppm	59Co ppm	60Ni ppm	69Ga ppm	72Ge ppm	75As ppm	82Se ppm	85Rb ppm	88Sr ppm
1a	Caerloggas 4/12	139	1	0	16	848	0	2	4	0	4	0	1	3
1b	Caerloggas 4/12	160	1	0	13	661	0	3	4	0	3	0	2	2
1c	Caerloggas 4/12	149	1	0	12	722	0	3	4	0	3	0	1	2
	Mean of Caerloggas 4/12	149	1	0	14	744	0	3	4	0	3	0	2	2
1a	Caerloggas 4/13	32	0	0	0	50	0	0	1	0	2	0	0	0
1b	Caerloggas 4/13	49	0	0	0	19	0	0	0	0	1	0	0	0
1c	Caerloggas 4/13	30	0	0	0	10	0	0	1	0	0	0	0	0
	Mean of Caerloggas 4/13	37	0	0	0	27	0	0	1	0	1	0	0	0
1a	Chysauster 4/30	6	0	0	1	350	0	0	1	0	0	0	0	2
1b	Chysauster 4/30	4	0	0	1	276	0	0	1	0	0	0	0	2
1c	Chysauster 4/30	15	1	0	8	2212	1	4	7	0	0	0	1	15
	Mean of Chysauster 4/30	8	0	0	3	946	0	2	3	0	0	0	0	6
1a	Crift Farm 4/11	114	3	3	52	10290	4	3	5	1	97	0	3	15
1b	Crift Farm 4/11	141	4	5	106	12300	8	5	7	1	132	0	5	20
1c	Crift Farm 4/11	123	5	6	61	8849	5	5	5	1	133	0	4	17
	Mean of Crift Farm 4/11	126	4	4	73	10480	6	5	6	1	120	0	4	17
2a	Crift Farm 4/11	94	3	4	37	6173	2	3	3	0	66	0	3	11
2b	Crift Farm 4/11	94	3	4	75	7504	3	2	4	0	94	0	4	13
2c	Crift Farm 4/11	95	3	4	307	8957	3	3	4	0	123	0	6	12
	Mean of Crift Farm 4/11	94	3	4	140	7545	3	3	4	0	94	0	4	12
1a	Dean Moor 3/48	695	30	5	59	19200	4	23	39	2	117	0	67	65
1b	Dean Moor 3/48	578	26	3	10	8875	2	17	19	1	25	0	41	8
1c	Dean Moor 3/48	592	23	3	14	7459	2	19	16	1	25	0	38	8
	Mean of Dean Moor 3/48	622	26	4	27	11850	3	20	24	2	56	0	48	27
2a	Dean Moor 3/48	428	31	3	32	7869	2	14	9	1	11	0	5	31
2b	Dean Moor 3/48	325	18	2	11	3214	1	10	3	1	8	0	4	8
2c	Dean Moor 3/48	322	16	4	23	5737	1	12	12	1	17	0	23	21
	Mean of Dean Moor 3/48	358	22	3	22	5607	1	12	8	1	12	0	11	20

Run	Label	47Ti ppm	51V ppm	52Cr ppm	55Mn ppm	56Fe ppm	59Co ppm	60Ni ppm	69Ga ppm	72Ge ppm	75As ppm	82Se ppm	85Rb ppm	88Sr ppm
3a	Dean Moor 3/48	252	41	4	10	2497	1	7	4	0	6	0	5	6
3b	Dean Moor 3/48	336	21	3	35	4171	1	5	5	0	11	0	7	15
3c	Dean Moor 3/48	406	24	5	13	3763	1	11	5	1	7	0	6	9
	Mean of Dean Moor 3/48	332	29	4	19	3477	1	8	4	1	8	0	6	10
4a	Dean Moor 3/48	275	10	3	34	3905	1	5	6	0	5	0	9	9
4b	Dean Moor 3/48	228	12	2	8	2166	1	6	4	0	5	0	8	3
4c	Dean Moor 3/48	227	14	4	22	3932	1	7	5	1	5	0	6	5
	Mean of Dean Moor 3/48	243	12	3	21	3334	1	6	5	0	5	0	8	6
1a	Upper Merrivale 4/10	6	1	0	10	1262	0	0	2	0	0	0	0	22
1b	Upper Merrivale 4/10	6	1	0	10	1090	0	0	2	0	0	0	0	18
1c	Upper Merrivale 4/10	1	0	0	3	364	0	0	1	0	0	0	0	8
	Mean of Upper Merrivale 4/10	4	1	0	8	905	0	0	1	0	0	0	0	16
2a	Upper Merrivale 4/10	0	0	0	2	51	0	0	0	0	0	0	0	2
2b	Upper Merrivale 4/10	1	0	0	3	318	0	0	0	0	0	0	0	9
2c	Upper Merrivale 4/10	29	6	0	58	4736	1	3	7	0	3	0	1	90
	Mean of Upper Merrivale 4/10	10	2	0	21	1702	0	1	2	0	1	0	0	33
1a	Metherel 4/14	543	13	1	402	12440	3	10	13	0	2	0	4	21
1b	Metherel 4/14	645	14	4	194	15530	3	11	14	1	3	0	11	26
1c	Metherel 4/14	792	17	6	93	17010	3	14	16	1	4	0	22	34
	Mean of Metherel 4/14	660	15	4	230	14990	3	12	14	1	3	0	12	27
2a	Metherel 4/14	799	26	11	96	13130	4	14	14	0	0	0	5	16
2b	Metherel 4/14	1075	30	12	116	12750	4	15	15	0	1	0	5	16
2c	Metherel 4/14	859	30	18	84	13150	4	15	15	0	1	0	4	15
	Mean of Metherel 4/14	911	29	13	99	13010	4	15	15	0	0	0	5	16

Run	Label	89Y ppm	90Zr ppm	93Nb ppm	95Mo ppm	101Ru ppm	103Rh ppm	105Pd ppm	107Ag ppm	111Cd ppm	118Sn ppm	121Sb ppm	125Te ppm	133Cs ppm
1a	Caerloggas 4/12	0	57	154	0	0	0	0	532	1	210800	2	1	1
1b	Caerloggas 4/12	0	61	170	0	0	0	0	584	1	230500	2	1	2
1c	Caerloggas 4/12	0	62	163	0	0	0	0	567	2	238000	2	1	2
	Mean of Caerloggas 4/12	0	60	162	0	0	0	0	561	1	226400	2	1	2
1a	Caerloggas 4/13	0	2	4	0	0	0	0	1	0	36510	0	0	0
1b	Caerloggas 4/13	0	5	6	0	0	0	0	0	0	17880	0	0	0
1c	Caerloggas 4/13	0	1	3	0	0	0	0	0	0	12060	0	0	0
	Mean of Caerloggas 4/13	0	2	4	0	0	0	0	0	0	22150	0	0	0
1a	Chysauster 4/30	0	0	2	0	0	0	0	0	0	13440	1	0	0
1b	Chysauster 4/30	0	0	2	0	0	0	0	0	0	11170	1	0	0
1c	Chysauster 4/30	0	1	4	0	0	0	0	1	0	13450	1	0	1
	Mean of Chysauster 4/30	0	0	3	0	0	0	0	0	0	12690	1	0	0
1a	Crift Farm 4/11	1	6	35	1	0	0	0	24	1	155600	6	2	1
1b	Crift Farm 4/11	11	10	38	1	0	0	0	35	2	158700	9	2	1
1c	Crift Farm 4/11	2	8	55	1	0	0	0	35	1	214600	6	2	1
	Mean of Crift Farm 4/11	5	8	43	1	0	0	0	31	1	176300	7	2	1
2a	Crift Farm 4/11	1	5	24	0	0	0	0	12	0	111700	5	0	1
2b	Crift Farm 4/11	2	5	20	2	0	0	0	18	0	96220	5	0	1
2c	Crift Farm 4/11	5	7	22	7	0	0	0	12	1	105100	6	0	1
	Mean of Crift Farm 4/11	2	5	22	3	0	0	0	14	0	104300	5	0	1
1a	Dean Moor 3/48	12	793	35	0	0	0	0	8	0	X	60	1	13
1b	Dean Moor 3/48	1	47	29	1	0	0	0	9	1	X	84	1	11
1c	Dean Moor 3/48	1	51	29	0	0	0	0	13	1	X	95	1	10
	Mean of Dean Moor 3/48	5	297	31	0	0	0	0	10	1	X	80	1	11
2a	Dean Moor 3/48	0	29	17	0	0	0	0	11	1	X	109	1	1
2b	Dean Moor 3/48	0	37	14	0	0	0	0	22	1	X	82	1	2
2c	Dean Moor 3/48	1	21	13	0	0	0	0	12	1	X	59	1	6
	Mean of Dean Moor 3/48	1	29	15	0	0	0	0	15	1	X	83	1	3

Run	Label	89Y ppm	90Zr ppm	93Nb ppm	95Mo ppm	101Ru ppm	103Rh ppm	105Pd ppm	107Ag ppm	111Cd ppm	118Sn ppm	121Sb ppm	125Te ppm	133Cs ppm
3a	Dean Moor 3/48	0	17	22	0	0	0	0	21	1	368000	78	1	3
3b	Dean Moor 3/48	1	19	32	0	0	0	0	21	1	324500	64	1	2
3c	Dean Moor 3/48	1	33	33	0	0	0	0	36	2	480100	123	1	2
	Mean of Dean Moor 3/48	1	23	29	0	0	0	0	26	1	390900	88	1	2
4a	Dean Moor 3/48	0	21	12	0	0	0	0	2	1	321300	48	1	2
4b	Dean Moor 3/48	0	25	15	0	0	0	0	4	1	434500	56	1	3
4c	Dean Moor 3/48	0	24	12	0	0	0	0	10	1	447100	94	1	2
	Mean of Dean Moor 3/48	0	23	13	0	0	0	0	5	1	400900	66	1	3
1a	Upper Merrivale 4/10	1	0	0	0	0	0	0	0	0	42	0	0	1
1b	Upper Merrivale 4/10	1	0	0	0	0	0	0	0	0	30	0	0	0
1c	Upper Merrivale 4/10	1	0	0	0	0	0	0	0	0	19	0	0	0
	Mean of Upper Merrivale 4/10	1	0	0	0	0	0	0	0	0	30	0	0	0
2a	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	5	0	0	0
2b	Upper Merrivale 4/10	10	0	0	0	0	0	0	0	0	22	0	0	0
2c	Upper Merrivale 4/10	5	0	0	0	0	0	0	0	0	162	1	0	1
	Mean of Upper Merrivale 4/10	5	0	0	0	0	0	0	0	0	63	0	0	1
1a	Metherel 4/14	1	2	1	0	0	0	0	1	0	132	1	0	2
1b	Metherel 4/14	2	7	2	0	0	0	0	1	0	254	2	0	5
1c	Metherel 4/14	2	10	3	0	0	0	0	0	0	315	1	0	11
	Mean of Metherel 4/14	2	6	2	0	0	0	0	1	0	233	1	0	6
2a	Metherel 4/14	1	27	1	0	0	0	0	1	0	147	1	0	2
2b	Metherel 4/14	1	18	3	0	0	0	0	1	0	276	1	0	2
2c	Metherel 4/14	1	24	2	0	0	0	0	2	0	313	2	0	2
	Mean of Metherel 4/14	1	23	2	0	0	0	0	1	0	245	1	0	2

Run	Label	137Ba ppm	139La ppm	140Ce ppm	141Pr ppm	146Nd ppm	147Sm ppm	153Eu ppm	157Gd ppm	159Tb ppm	163Dy ppm	165Ho ppm	166Er ppm	169Tm ppm	172Yb ppm
1a	Caerloggas 4/12	7	0	0	0	0	0	0	0	0	0	0	0	0	0
1b	Caerloggas 4/12	8	0	0	0	0	0	0	0	0	0	0	0	0	0
1c	Caerloggas 4/12	9	1	1	0	0	0	0	0	0	0	0	0	0	0
	Mean of Caerloggas 4/12	8	0	1	0	0	0	0	0	0	0	0	0	0	0
1a	Caerloggas 4/13	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1b	Caerloggas 4/13	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1c	Caerloggas 4/13	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean of Caerloggas 4/13	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1a	Chysauster 4/30	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1b	Chysauster 4/30	1	0	1	0	1	0	0	0	0	0	0	0	0	0
1c	Chysauster 4/30	2	0	1	0	0	0	0	0	0	0	0	0	0	0
	Mean of Chysauster 4/30	1	0	1	0	0	0	0	0	0	0	0	0	0	0
1a	Crift Farm 4/11	50	1	2	0	1	0	0	1	0	0	0	0	0	0
1b	Crift Farm 4/11	81	4	7	1	4	1	0	2	0	3	1	2	0	2
1c	Crift Farm 4/11	82	2	5	1	3	1	0	1	0	1	0	0	0	0
	Mean of Crift Farm 4/11	71	3	5	1	3	1	0	1	0	1	0	1	0	1
2a	Crift Farm 4/11	45	1	2	0	1	0	0	0	0	0	0	0	0	0
2b	Crift Farm 4/11	46	1	2	0	2	0	0	1	0	1	0	0	0	1
2c	Crift Farm 4/11	91	8	10	4	22	5	1	5	0	2	0	1	0	1
	Mean of Crift Farm 4/11	61	3	4	2	8	2	0	2	0	1	0	0	0	1
1a	Dean Moor 3/48	27	7	12	2	10	2	0	3	1	4	1	2	0	4
1b	Dean Moor 3/48	24	5	8	1	6	1	0	1	0	0	0	0	0	0
1c	Dean Moor 3/48	21	4	6	1	4	1	0	1	0	0	0	0	0	0
	Mean of Dean Moor 3/48	24	5	9	1	7	1	0	1	0	1	0	1	0	2
2a	Dean Moor 3/48	11	1	2	0	1	0	0	0	0	0	0	0	0	0
2b	Dean Moor 3/48	9	1	1	0	1	0	0	0	0	0	0	0	0	0
2c	Dean Moor 3/48	25	2	4	1	2	0	0	0	0	0	0	0	0	0
	Mean of Dean Moor 3/48	15	2	2	0	1	0	0	0	0	0	0	0	0	0

Run	Label	137Ba ppm	139La ppm	140Ce ppm	141Pr ppm	146Nd ppm	147Sm ppm	153Eu ppm	157Gd ppm	159Tb ppm	163Dy ppm	165Ho ppm	166Er ppm	169Tm ppm	172Yb ppm
3a	Dean Moor 3/48	17	1	1	0	1	0	0	0	0	0	0	0	0	0
3b	Dean Moor 3/48	19	2	3	0	2	0	0	0	0	0	0	0	0	0
3c	Dean Moor 3/48	25	1	2	0	1	0	0	0	0	0	0	0	0	0
	Mean of Dean Moor 3/48	21	1	2	0	1	0	0	0	0	0	0	0	0	0
4a	Dean Moor 3/48	18	1	2	0	1	0	0	0	0	0	0	0	0	0
4b	Dean Moor 3/48	17	1	2	0	1	0	0	0	0	0	0	0	0	0
4c	Dean Moor 3/48	25	1	1	0	1	0	0	0	0	0	0	0	0	0
	Mean of Dean Moor 3/48	20	1	2	0	1	0	0	0	0	0	0	0	0	0
1a	Upper Merrivale 4/10	0	1	2	0	2	1	0	1	0	1	0	0	0	1
1b	Upper Merrivale 4/10	0	0	1	0	1	0	0	1	0	1	0	0	0	1
1c	Upper Merrivale 4/10	0	0	1	0	1	1	0	2	0	1	0	1	0	1
	Mean of Upper Merrivale 4/10	0	0	1	0	1	1	0	1	0	1	0	0	0	1
2a	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2b	Upper Merrivale 4/10	0	6	15	4	24	12	2	13	2	12	2	6	1	7
2c	Upper Merrivale 4/10	0	1	4	1	3	1	0	1	0	2	0	1	0	1
	Mean of Upper Merrivale 4/10	0	2	6	2	9	5	1	5	1	5	1	2	0	3
1a	Metherel 4/14	11	2	4	0	1	0	0	0	0	0	0	0	0	0
1b	Metherel 4/14	21	4	7	1	3	1	0	1	0	1	0	0	0	0
1c	Metherel 4/14	27	6	10	1	5	1	0	1	0	1	0	0	0	1
	Mean of Metherel 4/14	20	4	7	1	3	1	0	1	0	1	0	0	0	0
2a	Metherel 4/14	9	3	5	1	3	1	0	1	0	1	0	0	0	1
2b	Metherel 4/14	12	3	7	1	4	1	0	0	0	0	0	0	0	1
2c	Metherel 4/14	21	3	6	1	3	1	0	0	0	0	0	0	0	0
	Mean of Metherel 4/14	14	3	6	1	3	1	0	0	0	0	0	0	0	1

Run	Label	175Lu ppm	178Hf ppm	181Ta ppm	182W ppm	185Re ppm	189Os ppm	193Ir ppm	195Pt ppm	197Au ppm	202Hg ppm	205Tl ppm	208Pb ppm	209Bi ppm	232Th ppm	238U ppm
1a	Caerloggas 4/12	0	7	34	1092	0	0	0	0	0	248	0	47	2	0	2
1b	Caerloggas 4/12	0	7	35	1058	0	0	0	0	0	235	0	48	2	0	1
1c	Caerloggas 4/12	0	7	31	1152	0	0	0	0	0	223	0	47	3	0	1
	Mean of Caerloggas 4/12	0	7	33	1100	0	0	0	0	0	235	0	47	2	0	2
1a	Caerloggas 4/13	0	1	9	615	0	0	0	0	0	47	0	10	1	0	1
1b	Caerloggas 4/13	0	4	30	516	0	0	0	0	0	19	0	11	2	0	2
1c	Caerloggas 4/13	0	1	15	335	0	0	0	0	0	10	0	8	1	0	1
	Mean of Caerloggas 4/13	0	2	18	488	0	0	0	0	0	25	0	10	2	0	2
1a	Chysauster 4/30	0	0	2	54	0	0	0	0	0	47	0	6	0	0	1
1b	Chysauster 4/30	0	0	2	117	0	0	0	0	0	30	0	5	1	0	1
1c	Chysauster 4/30	0	0	2	81	0	0	0	0	0	69	0	6	0	0	1
	Mean of Chysauster 4/30	0	0	2	84	0	0	0	0	0	48	0	6	0	0	1
1a	Crift Farm 4/11	0	0	2	248	0	0	0	0	3	3110	0	1807	209	1	12
1b	Crift Farm 4/11	0	0	2	611	0	0	0	0	4	3170	0	2200	115	3	18
1c	Crift Farm 4/11	0	0	3	661	0	0	0	0	4	3108	0	2069	121	2	17
	Mean of Crift Farm 4/11	0	0	2	507	0	0	0	0	4	3130	0	2025	149	2	16
2a	Crift Farm 4/11	0	0	2	468	0	0	0	0	3	2208	0	448	41	1	10
2b	Crift Farm 4/11	0	0	1	5630	0	0	0	0	2	2655	0	642	75	2	16
2c	Crift Farm 4/11	0	0	2	20150	0	0	0	0	4	2879	0	708	76	11	23
	Mean of Crift Farm 4/11	0	0	2	8748	0	0	0	0	3	2581	0	599	64	5	16
1a	Dean Moor 3/48	1	17	9	400	0	0	0	0	0	168	1	39	5	7	28
1b	Dean Moor 3/48	0	3	9	385	0	0	0	0	0	162	0	38	2	3	38
1c	Dean Moor 3/48	0	3	9	405	0	0	0	0	0	172	0	53	2	3	56
	Mean of Dean Moor 3/48	0	8	9	397	0	0	0	0	0	167	0	43	3	4	41
2a	Dean Moor 3/48	0	2	7	376	0	0	0	0	0	175	0	38	1	1	67
2b	Dean Moor 3/48	0	2	7	258	0	0	0	0	0	161	0	36	1	1	51
2c	Dean Moor 3/48	0	1	5	177	0	0	0	0	1	204	0	86	1	3	31
	Mean of Dean Moor 3/48	0	2	6	270	0	0	0	0	0	180	0	53	1	2	50

Run	Label	175Lu ppm	178Hf ppm	181Ta ppm	182W ppm	185Re ppm	189Os ppm	193Ir ppm	195Pt ppm	197Au ppm	202Hg ppm	205Tl ppm	208Pb ppm	209Bi ppm	232Th ppm	238U ppm
3a	Dean Moor 3/48	0	2	11	370	0	0	0	0	1	144	0	118	2	2	61
3b	Dean Moor 3/48	0	2	13	464	0	0	0	0	1	143	0	92	1	2	52
3c	Dean Moor 3/48	0	3	20	577	0	0	0	0	1	144	0	172	5	2	93
	Mean of Dean Moor 3/48	0	2	15	470	0	0	0	0	1	144	0	127	3	2	69
4a	Dean Moor 3/48	0	2	6	243	0	0	0	0	0	151	0	80	1	3	45
4b	Dean Moor 3/48	0	2	9	380	0	0	0	0	1	167	0	87	1	2	50
4c	Dean Moor 3/48	0	2	6	565	0	0	0	0	1	158	0	99	1	2	82
	Mean of Dean Moor 3/48	0	2	7	396	0	0	0	0	1	158	0	88	1	2	59
1a	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	20	0	1	0	3	1
1b	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	20	0	0	0	3	1
1c	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	45	0	0	0	2	1
	Mean of Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	28	0	0	0	3	1
2a	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0
2b	Upper Merrivale 4/10	1	0	0	1	0	0	0	0	0	37	0	1	0	26	5
2c	Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	90	0	1	0	4	1
	Mean of Upper Merrivale 4/10	0	0	0	0	0	0	0	0	0	46	0	1	0	10	2
1a	Metherel 4/14	0	0	0	4	0	0	0	0	1	173	0	66	1	6	3
1b	Metherel 4/14	0	0	1	7	0	0	0	0	0	163	0	82	1	10	7
1c	Metherel 4/14	0	1	1	10	0	0	0	0	0	145	0	71	1	16	11
	Mean of Metherel 4/14	0	0	1	7	0	0	0	0	0	160	0	73	1	11	7
2a	Metherel 4/14	0	2	0	4	0	0	0	0	0	172	0	45	1	4	4
2b	Metherel 4/14	0	1	1	12	0	0	0	0	1	168	0	50	1	5	3
2c	Metherel 4/14	0	1	0	8	0	0	0	0	1	172	0	42	1	5	3
	Mean of Metherel 4/14	0	1	0	8	0	0	0	0	1	170	0	46	1	5	3

Appendix 11: Composition of Tin Metal Samples determined by ICPMS pnq = present, not quantifiable X = detector swamped

Run	Label	7Li ppm	9Be ppm	11B ppm	23Na ppm	24Mg ppm	27Al ppm	29Si ppm	31P ppm	33S ppm	39K ppm	44Ca ppm	45Sc Ppm
1a	Carloggas 4/29	0	0	1	pnq	22	93	77	54	pnq	99	192	0
1b	Carloggas 4/29	0	0	0	pnq	2	26	pnq	12	pnq	52	19	0
1c	Carloggas 4/29	0	0	0	pnq	1	33	pnq	9	pnq	48	3	0
	Mean of Carloggas 4/29	0	0	0	pnq	8	51	77	25	pnq	66	72	0
1a	Upper Merrivale 4/32 inner	0	0	0	pnq	0	1	pnq	0	pnq	34	pnq	0
1b	Upper Merrivale 4/32 inner	0	0	0	pnq	0	0	pnq	0	pnq	47	pnq	0
1c	Upper Merrivale 4/32 inner	0	0	0	pnq	0	1	pnq	0	pnq	58	pnq	0
	Mean of Upper Merrivale 4/32 inner	0	0	0	pnq	0	1	pnq	0	pnq	46	pnq	0
2a	Upper Merrivale 4/32 outer	2	4	2	pnq	25	563	186	68	pnq	52	pnq	0
2b	Upper Merrivale 4/32 outer	1	6	3	pnq	31	776	461	143	pnq	104	pnq	0
2c	Upper Merrivale 4/32 outer	1	4	2	pnq	10	483	126	64	pnq	36	pnq	0
	Mean of Upper Merrivale 4/32 outer	1	5	2	pnq	22	607	258	92	pnq	64	pnq	0
1a	Upper Merrivale 4/33 outer	21	2	954	349	421	2028	4446	87	pnq	552	57	1
1b	Upper Merrivale 4/33 outer	12	1	379	111	189	1130	2564	55	pnq	365	0	0
1c	Upper Merrivale 4/33 outer	8	0	219	pnq	71	794	1179	20	pnq	304	0	0
	Mean of Upper Merrivale 4/33 outer	13	1	517	150	227	1317	2730	54	pnq	407	19	0
1a	Trevellas Porth 3/46 outer	3	2	54	2528	18280	1428	1402	664	272	1085	390	0
1b	Trevellas Porth 3/46 outer	2	2	46	2602	16510	1196	1176	589	pnq	1051	343	0
1c	Trevellas Porth 3/46 outer	2	1	43	2613	16840	1315	1186	589	pnq	1063	371	0
	Mean of Trevellas Porth 3/46 outer	2	2	47	2581	17210	1313	1255	614	41	1066	368	0
2a	Trevellas Porth 3/46 outer	2	1	73	2797	4783	3228	3242	142	237	1198	911	0
2b	Trevellas Porth 3/46 outer	1	1	70	2786	5079	2609	3383	135	pnq	1052	512	0
2c	Trevellas Porth 3/46 outer	5	1	85	2946	3957	3653	3409	223	pnq	1122	764	0
	Mean of Trevellas Porth 3/46 outer	2	1	76	2843	4606	3163	3345	167	237	1124	729	0
1a	Trevellas Porth 4/31 outer	0	32	33	2704	2081	2575	1756	561	pnq	971	1092	10
1b	Trevellas Porth 4/31 outer	0	33	27	2864	1264	2161	1530	566	pnq	995	1107	9
1c	Trevellas Porth 4/31 outer	0	25	19	2729	988	1628	1283	455	pnq	1035	1069	6
	Mean of Trevellas Porth 4/31 outer	0	30	26	2766	1444	2121	1523	527	pnq	1000	1089	8
2a	Trevellas Porth 4/31 outer	0	29	16	2392	730	2136	1279	367	pnq	721	1142	6
2b	Trevellas Porth 4/31 outer	0	32	15	2607	800	2450	1371	411	pnq	808	1273	10
2c	Trevellas Porth 4/31 outer	0	33	15	2631	793	2821	1546	470	pnq	815	986	14
	Mean of Trevellas Porth 4/31 outer	0	32	15	2543	774	2469	1399	416	pnq	781	1134	10

Run	Label	47Ti ppm	51V ppm	52Cr ppm	55Mn ppm	56Fe ppm	59Co ppm	60Ni ppm	65Cu ppm	66Zn ppm	69Ga ppm	72Ge ppm
1a	Carloggas 4/29	8	0	3	19	555	6	8	5	8	0	0
1b	Carloggas 4/29	2	0	0	5	161	1	2	1	3	0	0
1c	Carloggas 4/29	3	0	0	2	106	0	1	1	2	0	0
	Mean of Carloggas 4/29	4	0	1	9	274	3	4	2	4	0	0
1a	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	8	0	0	0
1b	Upper Merrivale 4/32 inner	0	0	0	0	0	0	1	17	0	0	0
1c	Upper Merrivale 4/32 inner	0	0	0	0	0	1	4	32	0	0	0
	Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	2	19	0	0	0
2a	Upper Merrivale 4/32 outer	8	0	0	3	103	0	0	1	2	0	0
2b	Upper Merrivale 4/32 outer	18	1	0	18	138	0	0	4	13	0	0
2c	Upper Merrivale 4/32 outer	5	0	0	5	71	0	0	1	3	0	0
	Mean of Upper Merrivale 4/32 outer	10	1	0	9	104	0	0	2	6	0	0
1a	Upper Merrivale 4/33 outer	97	3	1	31	2004	1	1	2	10	3	0
1b	Upper Merrivale 4/33 outer	81	2	0	20	1078	0	1	1	5	1	0
1c	Upper Merrivale 4/33 outer	17	0	0	4	279	0	0	0	1	0	0
	Mean of Upper Merrivale 4/33 outer	65	2	0	18	1120	0	0	1	5	2	0
1a	Trevellas Porth 3/46 outer	81	42	26	65	1956	6	50	3094	50470	1	0
1b	Trevellas Porth 3/46 outer	58	37	32	56	1783	5	42	2608	43340	1	0
1c	Trevellas Porth 3/46 outer	68	38	33	61	1931	6	43	2387	43010	1	0
	Mean of Trevellas Porth 3/46 outer	69	39	30	61	1890	6	45	2696	45610	1	0
2a	Trevellas Porth 3/46 outer	63	29	11	64	8403	3	23	637	14500	1	0
2b	Trevellas Porth 3/46 outer	47	23	7	55	5793	3	23	742	13120	1	0
2c	Trevellas Porth 3/46 outer	39	21	8	51	6103	3	20	665	11610	1	0
	Mean of Trevellas Porth 3/46 outer	50	24	9	57	6766	3	22	681	13080	1	0
1a	Trevellas Porth 4/31 outer	415	33	66	166	38610	13	28	2486	8964	7	3
1b	Trevellas Porth 4/31 outer	339	35	67	101	38580	11	25	2830	9043	6	6
1c	Trevellas Porth 4/31 outer	163	36	73	70	36430	9	19	2317	7535	4	3
	Mean of Trevellas Porth 4/31 outer	306	35	69	112	37870	11	24	2544	8514	6	4
2a	Trevellas Porth 4/31 outer	691	31	51	178	34190	11	22	2174	7651	2	1
2b	Trevellas Porth 4/31 outer	850	33	54	134	34140	11	22	2350	7419	3	2
2c	Trevellas Porth 4/31 outer	1451	33	48	123	31380	11	20	2748	7809	4	2
	Mean of Trevellas Porth 4/31 outer	998	33	51	145	33230	11	21	2424	7626	3	1

Run	Label	95Mo ppm	101Ru ppm	103Rh ppm	105Pd ppm	107Ag ppm	111Cd ppm	118Sn ppm	121Sb ppm	125Te ppm	133Cs ppm
1a	Carloggas 4/29	0	0	0	0	35	1	253300	0	1	0
1b	Carloggas 4/29	0	0	0	0	18	0	103300	0	0	0
1c	Carloggas 4/29	0	0	0	0	13	0	62780	0	0	0
	Mean of Carloggas 4/29	0	0	0	0	22	0	139800	0	0	0
1a	Upper Merrivale 4/32 inner	0	0	0	0	0	0	35060	12	0	0
1b	Upper Merrivale 4/32 inner	0	0	0	0	0	0	64670	24	0	0
1c	Upper Merrivale 4/32 inner	0	0	0	0	0	0	150800	41	0	0
	Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	83500	26	0	0
2a	Upper Merrivale 4/32 outer	0	0	0	0	0	0	12840	0	0	0
2b	Upper Merrivale 4/32 outer	0	0	0	0	1	0	67520	3	0	1
2c	Upper Merrivale 4/32 outer	0	0	0	0	0	0	20100	0	0	0
	Mean of Upper Merrivale 4/32 outer	0	0	0	0	0	0	33480	1	0	1
1a	Upper Merrivale 4/33 outer	0	0	0	0	0	0	6690	11	0	7
1b	Upper Merrivale 4/33 outer	0	0	0	0	0	0	2159	3	0	5
1c	Upper Merrivale 4/33 outer	0	0	0	0	0	0	811	1	0	2
	Mean of Upper Merrivale 4/33 outer	0	0	0	0	0	0	3220	5	0	5
1a	Trevellas Porth 3/46 outer	10	0	0	0	96	10	361700	6	1	1
1b	Trevellas Porth 3/46 outer	8	0	0	0	86	8	368000	6	1	1
1c	Trevellas Porth 3/46 outer	9	0	0	0	74	9	367800	6	1	1
	Mean of Trevellas Porth 3/46 outer	9	0	0	0	85	9	365800	6	1	1
2a	Trevellas Porth 3/46 outer	4	0	0	0	29	8	426600	1	1	1
2b	Trevellas Porth 3/46 outer	4	0	0	0	23	7	391700	1	1	1
2c	Trevellas Porth 3/46 outer	3	0	0	0	18	7	378600	1	1	1
	Mean of Trevellas Porth 3/46 outer	4	0	0	0	23	7	399000	1	1	1
1a	Trevellas Porth 4/31 outer	2	0	0	0	28	19	465800	4	1	0
1b	Trevellas Porth 4/31 outer	4	0	0	0	19	17	421200	4	1	0
1c	Trevellas Porth 4/31 outer	3	0	0	0	13	14	420600	4	1	0
	Mean of Trevellas Porth 4/31 outer	3	0	0	0	20	17	435900	4	1	0
2a	Trevellas Porth 4/31 outer	2	0	0	0	17	14	357000	4	1	0
2b	Trevellas Porth 4/31 outer	2	0	0	0	15	13	381800	4	1	0
2c	Trevellas Porth 4/31 outer	2	0	0	0	11	16	373800	4	1	0
	Mean of Trevellas Porth 4/31 outer	2	0	0	0	14	14	370900	4	1	0

Run	Label	137Ba ppm	139La ppm	140Ce ppm	141Pr ppm	146Nd ppm	147Sm ppm	153Eu ppm	157Gd ppm	159Tb ppm	163Dy ppm	165Ho ppm	166Er ppm	169Tm ppm	172Yb ppm
1a	Carloggas 4/29	5	0	0	0	0	0	0	0	0	0	0	0	0	0
1b	Carloggas 4/29	2	0	0	0	0	0	0	0	0	0	0	0	0	0
1c	Carloggas 4/29	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean of Carloggas 4/29	3	0	0	0	0	0	0	0	0	0	0	0	0	0
1a	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1b	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1c	Upper Merrivale 4/32 inner	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2a	Upper Merrivale 4/32 outer	2	1	1	0	1	0	0	1	0	1	0	0	0	0
2b	Upper Merrivale 4/32 outer	6	4	6	2	7	2	0	2	1	3	1	1	0	1
2c	Upper Merrivale 4/32 outer	2	1	2	1	2	1	0	1	0	1	0	0	0	0
	Mean of Upper Merrivale 4/32 outer	3	2	3	1	4	1	0	1	0	1	0	1	0	1
1a	Upper Merrivale 4/33 outer	15	11	32	4	13	3	0	3	0	3	0	1	0	2
1b	Upper Merrivale 4/33 outer	11	11	28	4	15	3	0	2	0	2	0	1	0	1
1c	Upper Merrivale 4/33 outer	5	3	10	1	4	1	0	1	0	1	0	0	0	0
	Mean of Upper Merrivale 4/33 outer	10	8	23	3	11	2	0	2	0	2	0	1	0	1
1a	Trevellas Porth 3/46 outer	14	4	3	1	6	2	0	2	0	1	0	1	0	1
1b	Trevellas Porth 3/46 outer	12	4	3	1	5	1	0	2	0	1	0	1	0	1
1c	Trevellas Porth 3/46 outer	13	5	5	1	8	2	0	2	0	2	0	1	0	1
	Mean of Trevellas Porth 3/46 outer	13	5	4	1	7	2	0	2	0	1	0	1	0	1
2a	Trevellas Porth 3/46 outer	17	4	4	1	4	1	0	1	0	1	0	0	0	0
2b	Trevellas Porth 3/46 outer	14	3	2	1	3	1	0	1	0	1	0	0	0	0
2c	Trevellas Porth 3/46 outer	18	3	3	1	3	1	0	1	0	1	0	0	0	1
	Mean of Trevellas Porth 3/46 outer	17	3	3	1	3	1	0	1	0	1	0	0	0	0
1a	Trevellas Porth 4/31 outer	23	91	54	27	141	34	7	30	4	23	4	10	1	9
1b	Trevellas Porth 4/31 outer	20	79	33	22	115	29	6	27	4	21	4	9	1	8
1c	Trevellas Porth 4/31 outer	27	80	30	21	110	28	6	26	4	19	3	8	1	7
	Mean of Trevellas Porth 4/31 outer	23	84	39	23	122	30	7	28	4	21	4	9	1	8
2a	Trevellas Porth 4/31 outer	22	82	31	20	110	27	6	24	3	19	3	8	1	7
2b	Trevellas Porth 4/31 outer	20	87	39	23	124	33	7	30	4	23	4	10	1	9
2c	Trevellas Porth 4/31 outer	21	88	46	25	131	35	7	33	5	26	5	11	1	10
	Mean of Trevellas Porth 4/31 outer	21	86	39	23	122	32	7	29	4	23	4	9	1	8

Run	Label	175Lu ppm	178Hf ppm	181Ta ppm	182W ppm	185Re ppm	189Os ppm	193Ir ppm	195Pt ppm	197Au ppm	202Hg ppm	205Tl ppm	208Pb ppm	209Bi ppm	232Th ppm	238U ppm
1a	Carloggas 4/29	0	0	0	0	0	0	0	0	0	200	0	57	1	0	0
1b	Carloggas 4/29	0	0	0	0	0	0	0	0	0	146	0	35	1	0	0
1c	Carloggas 4/29	0	0	0	0	0	0	0	0	0	114	0	23	0	0	0
	Mean of Carloggas 4/29	0	0	0	0	0	0	0	0	0	153	0	39	1	0	0
1a	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	16	0	4	112	0	0
1b	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	22	0	5	168	0	0
1c	Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	1	35	0	9	218	0	0
	Mean of Upper Merrivale 4/32 inner	0	0	0	0	0	0	0	0	0	24	0	6	166	0	0
2a	Upper Merrivale 4/32 outer	0	0	0	14	0	0	0	0	0	0	0	14	1	1	3
2b	Upper Merrivale 4/32 outer	0	0	0	34	0	0	0	0	0	0	1	58	5	1	11
2c	Upper Merrivale 4/32 outer	0	0	0	14	0	0	0	0	0	0	0	26	1	1	4
	Mean of Upper Merrivale 4/32 outer	0	0	0	21	0	0	0	0	0	0	0	32	2	1	6
1a	Upper Merrivale 4/33 outer	0	1	3	71	0	0	0	0	0	22	0	13	6	13	14
1b	Upper Merrivale 4/33 outer	0	1	2	47	0	0	0	0	0	8	0	9	4	8	8
1c	Upper Merrivale 4/33 outer	0	0	1	21	0	0	0	0	0	7	0	10	4	4	5
	Mean of Upper Merrivale 4/33 outer	0	1	2	46	0	0	0	0	0	12	0	11	4	8	9
1a	Trevellas Porth 3/46 outer	0	0	0	17	0	0	0	0	0	6386	0	940	57	3	4
1b	Trevellas Porth 3/46 outer	0	0	0	16	0	0	0	0	0	5964	0	800	55	2	3
1c	Trevellas Porth 3/46 outer	0	0	0	15	0	0	0	0	0	5484	0	737	55	3	4
	Mean of Trevellas Porth 3/46 outer	0	0	0	16	0	0	0	0	0	5945	0	826	56	3	4
2a	Trevellas Porth 3/46 outer	0	0	0	10	0	0	0	0	0	3034	0	1213	3	5	8
2b	Trevellas Porth 3/46 outer	0	0	0	10	0	0	0	0	0	3014	0	849	2	4	9
2c	Trevellas Porth 3/46 outer	0	0	0	8	0	0	0	0	0	2943	0	830	3	4	12
	Mean of Trevellas Porth 3/46 outer	0	0	0	9	0	0	0	0	0	2997	0	964	3	4	10
1a	Trevellas Porth 4/31 outer	1	7	25	7427	0	0	0	0	1	676	11	3851	72	16	19
1b	Trevellas Porth 4/31 outer	1	6	15	9679	0	0	0	0	1	695	11	3788	90	16	16
1c	Trevellas Porth 4/31 outer	1	4	9	10630	0	0	0	0	1	704	8	3267	69	11	12
	Mean of Trevellas Porth 4/31 outer	1	5	17	9244	0	0	0	0	1	692	10	3635	77	15	16
2a	Trevellas Porth 4/31 outer	1	30	3	2690	0	0	0	0	0	1293	5	2644	33	46	24
2b	Trevellas Porth 4/31 outer	1	37	3	3291	0	0	0	0	1	1098	7	3187	77	51	18
2c	Trevellas Porth 4/31 outer	1	58	5	3886	0	0	0	0	0	944	10	3549	56	82	24
	Mean of Trevellas Porth 4/31 outer	1	42	4	3289	0	0	0	0	0	1112	8	3127	56	60	22

Appendix 13: Analysis of Recently Discovered Slag from High Down and East Okement Farm

The results of the analysis of recent finds of slag from two previously unknown sites are presented. Data were obtained too late for inclusion in the main text.

A13.1: The Finds

Five fragments of slag were discovered on 4/5/08 by Tom Greeves in an eroding waste heap by the bank of the River Lyd at High Down (SX5316885636). Greeves reports that there is no sign of a mill, furnace or other structure in the vicinity, nor is there any record of smelting in the area. Greeves suggests that the slag may have been disturbed when later tinners dug a trial pit (pers comm. 5/5/08).

Three pieces of slag were discovered by Lis Greeves in 2009 in a molehill in a field at East Okement Farm (SX6065091803), on the left (west) bank of the East Okement River. The slag was located 20-30m from the vestigial remains of a possible mill building, served by a leat (T. Greeves pers comm. March 2009; Greeves 2010b).

A13.2: Methods of Examination

Three pieces of slag from High Down and two pieces from East Okement Farm were cold mounted in resin, polished using graded papers down to 1 μm.

Digital images of the East Okement slag, at a range of objective magnifications between 2.5x and 40x, were obtained using a Nikon Optiphot reflected light microscope and Fire-i imaging software.

All the samples were subsequently carbon coated for backscatter electron imaging with a Fei Quanta 400 scanning electron microscope.

Energy dispersive X-ray spectra were obtained using the Fei Quanta 400 scanning electron microscope with an Oxford Instruments INCAx-Sight EDX system. Chemical compositions were determined from the spectra obtained using Oxford SEMQuant software. Multiple area scans of the slag matrix were made in order to obtain information for the bulk composition of the sample at points across the surface of each sample. As far as was possible scans avoided tin prills and mineral inclusions. The results are given in Tables A13.2-A13.6. Table A13.7 contains an analysis of adjacent flow bands in two of the High Down samples. Analysis was also carried out on mineral inclusions (Tables A13.8 and A13.9) and metallic prills (Tables A13.10 and A13.11).

A13.3: Results

A13.3.1: Description of Samples

Figure A13.1: Slag from High Down

Figure A13.2: Slag from East Okement Farm

Table A13.1: Description of Slag Samples

	High Down	**East Okement Farm**
Mass of samples	0.1g, 1.1g, 1.3g, 2.3g, 3.5g	0.3g, 0.8g, 3.2g
Colour	Black	Black
Lustre	Glassy	Glassy
Fracture	Conchoidal	Conchoidal
Weathering	Occasional patches of a light brown weathering product on the surface. Appear to have undergone relatively recent breakage, as some surfaces fresh and un-weathered.	Two fragments appear to have undergone relatively recent breakage, as some surfaces were fresh and un-weathered. Surface of one fragment weathered to a greyish-cream colour.
Morphology	Rod-like morphology, now much truncated, but with a slightly curved cross-section.	The weathered fragment appears originally to have had a rod-like morphology, but with an arced cross-section.
Mineral Inclusions	Several inclusions of vitrified mineral crystal, measuring between 1 and 3 mm.	Several inclusions of vitrified mineral crystal, measuring between 1 and 6 mm.
Prills	Many sub-millimetre metallic prills seen during polishing of the samples.	None observed.

A13.3.2: Microstructure

The three High Down samples mounted for examination with the scanning electron microscope were shown to have a glassy microstructure, with clear flow banding, indicating areas of different composition (Figure A13.3).

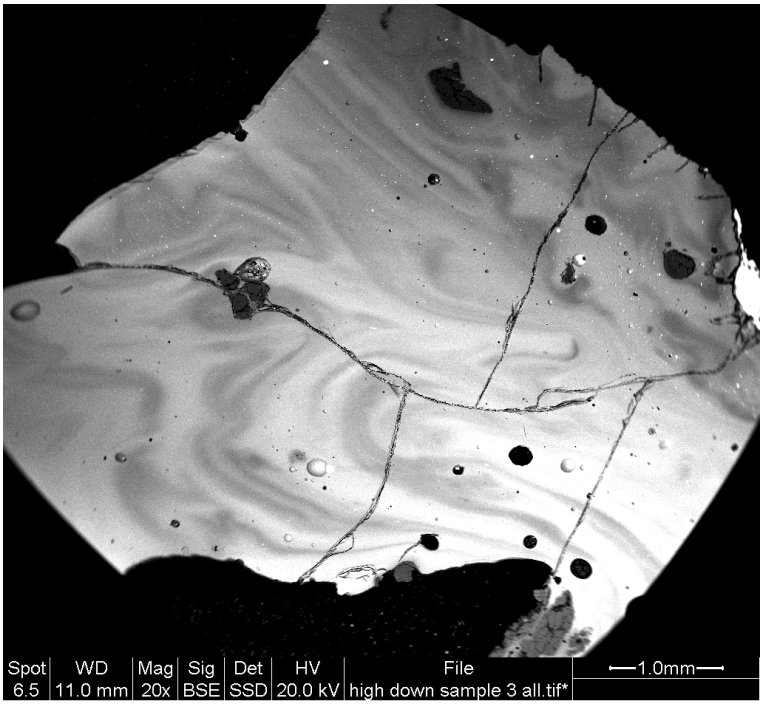


Figure A13.3: Scanning electron micrograph of High Down slag, sample 8/02, showing glassy slag with distinct flow banding. Dark vesicles are visible on the right hand side of the slag. Abundant small prills, appearing white, are concentrated in the top right hand corner of the sample.

All contained abundant metallic prills embedded in the slag matrix, the majority of which measured <2 μm in diameter, although some larger prills measuring approximately 10 μm were also present (Figure A13.4). The majority of the prills appeared to be circular, but some were irregularly shaped. At high magnifications most prills appeared to have a mottled surface (Figure A13.5).

Inclusions of vitrified gangue mineral crystals were also observed (Figure A13.6).

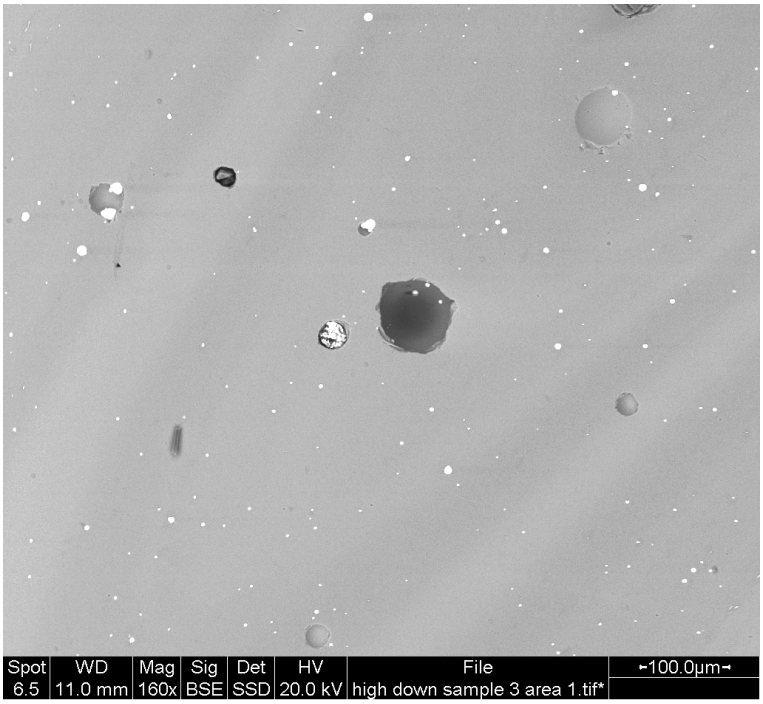


Figure A13.4: Scanning electron micrograph of High Down slag, sample 8/03, showing abundant small prills, appearing white, embedded in the glassy slag matrix. Some dark vesicles are also visible.

The two East Okement Farm samples were shown to have a glassy microstructure, with faint flow banding visible under back-scattered electron imaging.

The slag was relatively free of metallic prills. Only two prills, measuring c.10 μm in diameter, were observed in one of the samples. These were circular in shape. At high magnifications the prills appeared to have a mottled surface.

Inclusions of vitrified gangue mineral crystals and ovoid patches of a lighter phase within the slag were also observed in the second sample.

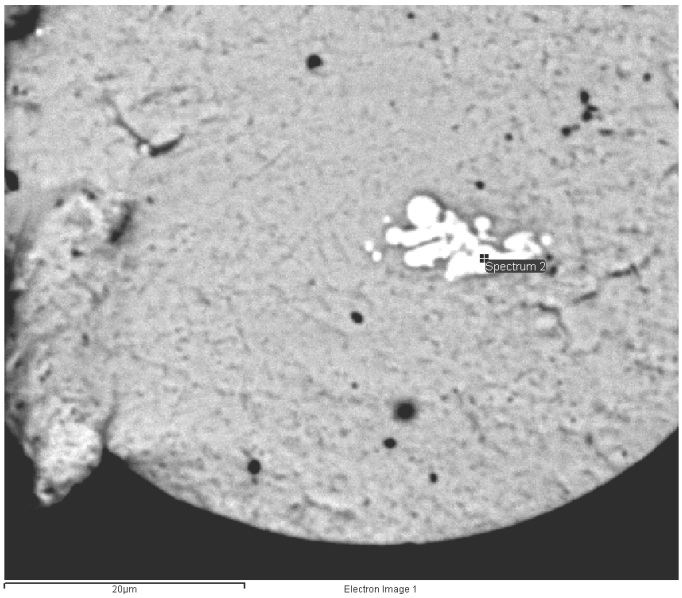


Figure A13.5: Scanning electron micrograph of a prill in High Down sample 8/02. The surface of the prill, which is impure tin, appears grey and mottled; the lighter irregular patch is composed of tungsten.

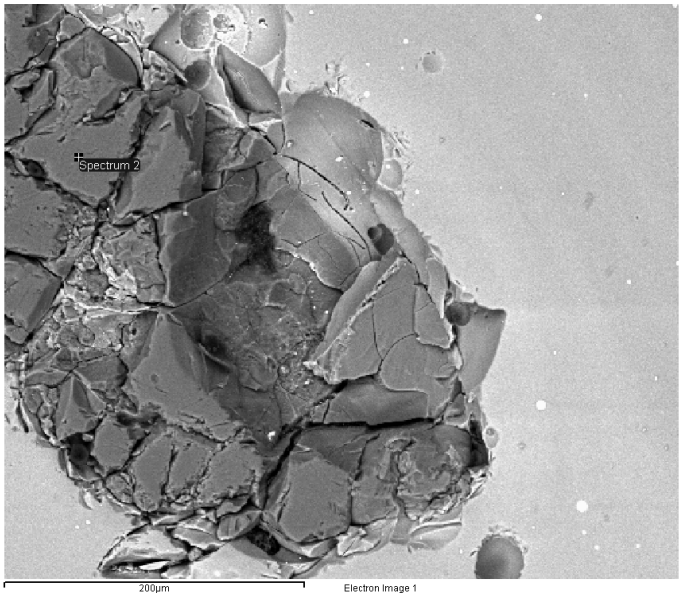


Figure A13.6: Scanning electron micrograph of a quartz inclusion in High Down sample 8/03.

A13.3.3: Compositional Analysis

Results of area analysis of the slag matrix of the three High Down samples are presented in Tables A13.2-A13.4; results from the East Okement Farm samples are given in Tables A13.5 and A13.6.

Table A13.2: Composition of High Down Slag: Matrix of Sample 8/01 (wt%)

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean
Na_2O	1.39	1.59	1.43	1.43	1.34	1.47	1.44
MgO	3.53	3.75	3.58	3.51	3.71	3.57	3.61
Al_2O_3	16.17	15.72	15.87	15.68	15.97	16.27	15.95
SiO_2	55.23	55.46	55.97	56.46	55.90	56.40	55.90
P_2O_5	0.74	0.66	0.74	0.72	0.83	0.63	0.72
K_2O	1.68	1.59	1.67	1.56	1.70	1.62	1.64
CaO	0.72	0.81	0.70	0.81	0.70	0.59	0.72
TiO_2	4.80	4.71	4.63	4.80	4.65	5.10	4.78
V_2O_5	0.38	0.05	0.01	0.13	0.10	nd	0.13
MnO	1.21	1.13	0.86	1.08	0.93	1.04	1.04
FeO	8.03	8.21	8.21	7.88	7.73	7.83	7.98
CuO	nd	0.03	nd	nd	0.01	nd	0.02
As_2O_3	0.25	nd	nd	0.34	0.06	0.03	0.17
ZrO_2	1.24	0.73	0.78	0.62	0.86	0.81	0.84
MoO_3	nd	0.13	0.08	0.24	0.18	0.17	0.16
SnO	5.09	5.03	5.04	4.83	4.86	5.02	4.98
Sb_2O_3	nd	0.07	nd	0.01	nd	nd	0.04
WO_3	0.14	0.35	0.45	nd	0.41	nd	0.34
Sum	100.60	100.02	100.02	100.10	99.94	100.55	100.46

nd = not detected

The slag from both sites is alumino-silicate glass containing variable amounts of other metallic and non-metallic elements, particularly tin and iron, which are probably present as silicates. The mean tin oxide content of the High Down slag is fairly low at between c.5 and 9%. The mean iron oxide in each sample is slightly higher than the tin oxide content, being present at levels between c.8 and 12%. Titanium oxide content is relatively low at 4-5%. At c.1%, the tungsten content of the slag is quite low.

Table A13.3: Composition of High Down Slag: Matrix of Sample 8/02 (wt%)

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean
Na_2O	1.22	1.10	1.14	1.06	1.05	1.16	1.12
MgO	3.34	3.10	3.20	3.61	3.16	3.21	3.27
Al_2O_3	16.48	16.01	15.46	16.23	15.69	15.70	15.93
SiO_2	51.34	49.82	47.39	50.46	48.35	48.17	49.26
P_2O_5	1.00	0.61	0.82	0.84	0.60	0.86	0.79
K_2O	1.43	1.45	1.41	1.43	1.36	1.22	1.38
CaO	0.96	0.71	0.88	0.78	0.72	0.93	0.83
TiO_2	3.86	3.78	3.62	4.01	3.66	3.65	3.76
V_2O_5	0.16	0.08	0.01	0.08	0.30	0.09	0.12
MnO	1.15	1.13	1.14	1.12	1.20	1.30	1.17
FeO	11.57	11.79	11.49	11.32	11.25	11.53	11.49
CuO	nd	0.19	0.08	0.06	0.31	nd	0.16
As_2O_3	nd	0.11	0.10	nd	0.00	0.12	0.08
ZrO_2	nd	0.15	0.09	0.37	0.29	0.39	0.26
MoO_3	nd	0.19	0.09	nd	0.14	0.07	0.12
SnO	6.75	8.83	11.60	7.90	10.82	10.49	9.40
Sb_2O_3	nd	nd	nd	0.10	nd	0.21	0.16
WO_3	1.01	1.10	1.44	1.04	1.12	0.69	1.07
Sum	100.27	100.15	99.96	100.41	100.02	99.79	100.37

Table A13.4: Composition of High Down Slag: Matrix of Sample 8/03 (wt%)

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Mean
Na_2O	1.49	1.34	1.34	1.29	1.42	1.38	1.38
MgO	3.61	3.71	3.67	3.49	3.69	3.72	3.65
Al_2O_3	15.15	15.06	15.05	15.15	14.78	14.79	15.00
SiO_2	51.86	52.49	53.76	52.55	52.33	53.03	52.67
P_2O_5	0.49	0.73	0.88	0.82	0.84	0.97	0.79
K_2O	1.78	1.86	1.75	1.65	1.54	1.67	1.71
CaO	0.63	0.52	0.71	0.66	0.65	0.75	0.65
TiO_2	5.17	5.48	5.10	5.30	5.64	5.39	5.35
V_2O_5	0.23	0.04	0.08	0.18	nd	nd	0.13
MnO	0.91	0.75	0.89	0.91	0.90	0.85	0.87
FeO	8.83	8.71	7.90	8.03	9.04	8.30	8.47
CuO	0.03	nd	0.25	0.10	nd	nd	0.13
As_2O_3	0.17	nd	nd	0.22	nd	0.00	0.13
ZrO_2	1.33	1.53	1.23	1.24	1.35	1.67	1.39
MoO_3	nd	nd	0.18	0.14	0.57	0.63	0.38
SnO	7.08	7.33	5.90	6.47	6.16	5.94	6.48
Sb_2O_3	nd	nd	0.22	0.56	nd	nd	0.39
WO_3	1.55	0.95	0.49	0.98	0.95	0.18	0.85
Sum	100.31	100.50	99.40	99.74	99.86	99.27	100.41

Table A13.5: Composition of East Okement Farm Slag: Matrix of Sample 9/01

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
Na_2O	1.1	1.2	1.1	1.1	1.1	1.1
MgO	3.0	2.9	2.8	2.9	2.5	2.8
Al_2O_3	12.2	11.9	12.0	12.3	11.9	12.1
SiO_2	46.9	46.0	46.6	46.8	45.3	46.3
P_2O_5	0.9	0.7	0.5	0.7	0.6	0.7
K_2O	1.8	1.7	1.9	2.0	1.7	1.8
CaO	1.2	1.1	0.9	1.1	1.3	1.1
TiO_2	5.0	4.8	5.0	5.0	4.7	4.9
V_2O_5	0.0	0.1	0.2	0.0	0.1	0.1
MnO	1.2	1.2	0.9	1.0	0.9	1.0
FeO	10.5	10.8	10.6	10.8	10.8	10.7
CuO	nd	nd	0.0	0.1	0.0	0.0
As_2O_3	0.2	nd	0.0	0.1	nd	0.1
ZrO_2	1.0	0.8	1.1	1.1	0.9	1.0
MoO_3	nd	nd	0.2	nd	0.2	0.2
SnO	11.3	13.2	12.8	12.1	13.3	12.5
Sb_2O_3	0.4	nd	nd	nd	0.6	0.5
WO_3	3.3	4.5	3.3	3.3	4.2	3.7
Sum	99.9	100.8	99.9	100.2	100.1	100.7

Table A13.6: Composition of East Okement Farm Slag: Matrix of Sample 9/02

Oxide	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
Na_2O	1.3	1.1	1.0	1.1	1.3	1.2
MgO	2.7	3.1	2.8	3.0	2.9	2.9
Al_2O_3	12.4	12.4	12.3	12.2	12.5	12.3
SiO_2	48.2	47.8	48.0	49.0	50.0	48.6
P_2O_5	0.7	0.6	0.9	0.9	0.8	0.8
K_2O	1.8	1.8	1.6	1.6	1.9	1.8
CaO	1.1	1.0	1.2	1.1	1.1	1.1
TiO_2	5.3	5.2	5.1	5.0	5.1	5.1
V_2O_5	0.1	0.1	0.1	0.0	0.0	0.1
MnO	1.1	1.0	1.2	1.1	1.1	1.1
FeO	11.0	11.1	10.9	11.3	10.6	11.0
CuO	0.1	0.0	nd	nd	0.1	0.1
As_2O_3	0.0	nd	nd	0.2	nd	0.1
ZrO_2	1.3	1.3	1.2	0.8	0.9	1.1
MoO_3	0.1	0.0	0.3	nd	nd	0.1
SnO	10.0	10.5	10.5	10.2	8.9	10.0
Sb_2O_3	nd	nd	nd	nd	0.1	0.1
WO_3	2.8	3.0	3.2	3.1	2.6	2.9
Sum	99.9	100.1	100.2	100.6	99.9	100.3

The East Okement slag has a moderate mean tin oxide content, between c.9 and 13.5%. The mean iron oxide content in each sample is roughly similar to the tin oxide content, being present at levels between c.10-11%. Titanium oxide content is relatively low at c.5%. At c.2 – 4.5%, the tungsten content of the slag is relatively low.

Table A13.7: Chemical Composition of Flow Bands in High Down Slag (wt%)

Oxide	Dark band, sample 8/02 area 4	Light band, sample 8/02 area 4	Dark band, sample 8/03 area 1	Light band, sample 8/03 area 1	Dark band sample 8/03 area 1
Na_2O	1.34	0.88	1.51	1.31	1.58
MgO	3.17	3.05	3.49	3.45	3.68
Al_2O_3	16.89	15.00	15.21	14.70	15.51
SiO_2	53.24	45.70	53.24	52.00	53.76
P_2O_5	1.04	0.78	0.80	0.77	0.73
K_2O	1.66	1.17	1.64	1.52	1.80
CaO	0.87	0.62	0.72	0.73	0.62
TiO_2	3.74	3.67	5.52	5.52	5.56
V_2O_5	0.18	0.03	nd	0.08	0.07
MnO	1.28	1.18	1.11	0.85	0.94
FeO	10.28	12.51	8.71	9.17	8.68
CuO	0.08	0.14	0.03	0.08	0.10
As_2O_3	0.03	0.15	0.06	nd	nd
ZrO_2	0.08	0.22	1.40	1.38	1.15
MoO_3	0.20	0.05	nd	nd	nd
SnO	5.71	13.29	6.43	7.91	6.33
Sb_2O_3	nd	nd	nd	nd	nd
WO_3	nd	1.84	0.09	0.81	0.00
Sum	99.79	100.28	99.96	100.28	100.51

Analysis of adjacent flow bands within two of the High Down samples showed that the slag is heterogeneous; light and dark flow bands have slightly different compositions, but the extent to which various elements partition within the slag is variable. The results presented in Table A13.7 indicate that the light flow bands contain enhanced levels of tin, iron and tungsten, whereas adjacent darker bands have enhanced levels of silicon and aluminium.

Table A13.8: Composition of Mineral Inclusions in High Down Slag (wt%)

Oxide	Sample 8/01	Sample 8/02	Sample 8/03
Na_2O	0.00	nd	0.13
MgO	nd	0.02	nd
Al_2O_3	nd	nd	0.01
SiO_2	102.67	103.29	102.95
P_2O_5	0.29	0.12	nd
K_2O	0.01	nd	0.08
CaO	nd	nd	0.00
TiO_2	0.04	nd	0.04
V_2O_5	nd	0.04	0.06
MnO	0.01	nd	nd
FeO	0.07	0.09	0.13
CuO	0.01	0.03	nd
As_2O_3	0.01	nd	0.00
ZrO_2	nd	nd	nd
MoO_3	0.39	0.12	0.03
SnO	0.20	0.14	0.05
Sb_2O_3	0.02	nd	nd
WO_3	nd	nd	nd
Sum	103.72	103.85	103.48

Table A13.9: Composition of Mineral Inclusions in East Okement Farm Slag

	Sample 9/01			Sample 9/02
Oxide	Inclusion 1	Inclusion 2	Inclusion 3	Inclusion 1
Na_2O	0.0	nd	4.4	nd
MgO	0.0	0.0	nd	0.0
Al_2O_3	nd	nd	16.6	0.0
SiO_2	34.0	103.4	70.2	33.7
P_2O_5	nd	0.1	0.1	nd
K_2O	nd	nd	8.8	0.0
CaO	0.1	nd	0.3	0.0
TiO_2	nd	0.0	0.2	0.1
V_2O_5	0.1	0.0	0.1	0.0
MnO	nd	0.1	0.1	0.0
FeO	0.2	0.0	0.2	0.1
CuO	nd	nd	nd	nd
As_2O_3	0.1	nd	0.1	0.2
ZrO_2	64.3	nd	nd	63.1
MoO_3	nd	0.0	nd	0.3
SnO	nd	0.0	0.1	nd
Sb_2O_3	0.0	0.0	nd	nd
WO_3	1.3	Nd	nd	1.3
Sum	100.1	103.7	101.0	99.0

All the mineral inclusions in the High Down slag are composed of silicon, and thus are probably relic crystals of quartz. Quartz (9/01 Inclusion 2) also occurs in the East Okement Farm slag, but zirconia (9/01 Inclusion 1 and 9/02) and possibly Na K feldspar (9/01 Inclusion 3) are also present.

Table A13.10: Composition of Metallic Prills in High Down Slag (wt%)

	Sample 8/01				**Sample 8/02**		
Element	Prill 1	Prill 2 dark	Prill 2 light	Prill 3	Prill 1 dark	Prill 1 light	Prill 2
Fe	0.96	1.18	1.25	1.38	0.22	0.52	0.88
Cu	nd	nd	0.04	0.13	nd	0.05	0.24
As	0.13	0.28	0.19	0.23	nd	0.30	0.10
Sn	0.76	95.90	3.03	97.39	100.09	1.04	39.80
Sb	nd	nd	nd	nd	nd	nd	nd
W	98.24	3.18	95.62	1.53	0.50	98.26	59.45
Sum	100.09	100.54	100.13	100.66	100.81	100.17	100.47
Prill size	**c.10 μ**	**c.4 μ**		**c.3 μ**	**c.50 μ**		**c.10 μ**
Scan type	Area	Spot	Spot	Spot	Area	Spot	Area

	Sample 8/03					
Element	Prill 1 light	Prill 1 dark	Prill 2 light	Prill 3 light	Prill 3 dark	Prill 4 light
Fe	nd	41.19	0.10	1.39	0.40	0.56
Cu	0.13	nd	nd	0.18	0.18	0.19
As	nd	0.48	0.07	0.12	0.11	0.31
Sn	101.17	58.04	99.88	1.06	95.76	98.19
Sb	nd	nd	nd	nd	nd	nd
W	0.19	0.71	0.81	97.39	4.54	1.80
Sum	101.49	100.42	100.86	100.14	100.99	101.05
Prill size	**c.100 μ**		**c.50 μ**	**c.50 μ**		**c.10 μ**
Scan type	Spot	Spot	Spot	Spot	Spot	Spot

In the High Down slag, the prills analysed were of widely varying size. In most cases backscatter electron imaging showed the prills to have a mottled surface appearance.

Spot analysis of these phases indicated that the prills were composed of more than one metallic element. The major elements present are tin, iron and tungsten.

In sample 8/01 prill 1 is tungsten only; prill 2 had a darker-appearing tin phase and a lighter tungsten phase; prill 3 was poor quality tin. In sample 8/02 prill 1 had a dark tin phase and a light tungsten phase; prill 2 was apparently a mix of tin and tungsten (no separate phases were observed but it is probable that the tin and tungsten occupy separate areas as the two metals are extremely insoluble). In sample 8/03 prill 1 had a light tin phase and a darker tin-iron alloy phase; the part of prill 2 analysed was relatively pure tin, another phase (probably tin-iron) was not analysed; prill 3 contained a lighter tungsten phase and a dark tin phase with a little tungsten; prill 4 was impure tin.

Arsenic and copper were present at only trace levels. Antimony was not detected.

Table A13.11: Composition of Metallic Prill in East Okement Farm, Sample 9/02 (wt%)

Element	Bulk	Phase 1	Phase 2
Fe	7.1	1.1	2.9
Cu	0.1	0.0	0.1
As	0.2	nd	0.1
Sn	56.4	93.6	16.0
Sb	nd	nd	0.4
W	35.5	nd	83.0
Sum	99.3	94.7	102.4

The single prill in the East Okement slag that was analysed was relatively small, measuring c.10 μm in diameter. The major elements present were tin, iron and tungsten. Backscatter imaging showed the prill to have the mottled surface appearance indicative of multiple metallic elements being present. Phase 1 was relatively pure tin metal. Phase 2 was a mix of tin and tungsten with some iron. Separate areas of tin and

tungsten could not be distinguished within this phase. It is possible that tin from an underlying phase was being detected. Tungsten is a siderophilic element, so is probably alloyed with the iron.

Antimony, arsenic and copper were present at only trace levels.

A13.4: Summary

The suggestion of a rod-like morphology to the slag fragments from High Down is indicative of a material that had a relatively high viscosity when molten, as is its glassy microstructure and the presence of striations. Although the amount of tin chemically combined in the slag is relatively low compared to other Dartmoor slags, and tungsten content is also relatively low, the ratio of heavy elements (which increase viscosity) to lighter elements, such as iron, titanium and calcium, (which reduce it) is low. Calculated iron to tin ratios for the three High Down samples are 1.6, 1.2 and 1.3. Sample 8/01, which had the highest ratio and was therefore theoretically more fluid, exhibited only very faint flow banding, whereas in the two samples with lower ratios, the striations were very marked. The ratios calculated are typical for the area of Dartmoor in which the samples were discovered. Other sites in the north-western corner of Dartmoor (e.g. Doe Tor Green, South Hill, Teignhead Farm, Outer Down) have previously been shown to have Fe/Sn ratios in the range 1.0 to 1.7, and also have microstructures suggesting higher viscosities.

The nearest known smelting site to High Down is the 16th Century tin mill at Doe Tor Green (SX53338524). Slag from this site has a similar composition to the High Down slag: tin contents are c.10% and 5-9% respectively; tungsten contents are low at c.1%; tungsten appears to be concentrated in the metallic prills rather than the slag, which is unusual.

Owing to its high viscosity metallic prills are very common in the High Down slag; many of these have an irregular shape or a mottled appearance when viewed using backscattered electron imaging, which indicates two or more different metals or alloy phases within a prill. Analysis indicates that the metallic prills are not pure tin, but also contain iron and tungsten. Tin and iron are mutually soluble at the concentrations present, and thus form crystals of the tin-iron alloy known as hardhead embedded in a matrix of pure tin; tungsten and iron are also mutually soluble. Tungsten, however, is not at all soluble in tin and the presence of these two metals can cause a prill to fail to coalesce, thus causing it to have an irregular shape rather than be spherical.

The origin of the slag cannot be determined with any certainty. The similarity of the High Down slag to the Doe Tor Green slag could indicate that the former was also produced in a blowing house; the location of the find is consistent with this interpretation. The presence of tungsten and iron in the prills is certainly not suggestive of gently reducing conditions. However, no blowing house is known to have been situated in the area, which leaves open the possibility that the slag may be from a smelting furnace that operated in a period prior to the introduction of water power. Its morphology and microstructure are similar to those of early slags, and it also has a coating of golden-brown weathering product, which is probably silica or 'hydrogen glass', and this appears to occur mainly, though not exclusively, on early slags. It is notable that this slag, at 49-55%, does have an extremely high SiO_2 content, compared to other blowing house slags where levels of silica are in the 20-40% range.

The East Okement slag was discovered close to the remains of a possible blowing house, and the composition of this slag is consistent with it having been produced by this technology, again bearing some physical and compositional similarity to the slag

from nearby Doe Tor Green, which is, like the East Okement Farm site, located along the northern edge of Dartmoor. The partitioning of tungsten into the prills is the most notable feature common to slag from both sites. The closest site to East Okement Farm is Taw River (SX62059197). Slags from the two sites have similar iron oxide contents (c.11%) and some samples from Taw River have similar tin oxide and tungsten oxide contents (c.10% and c.3% respectively), but there is no sign of tungsten in prills in the Taw River slag.

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DRO	Devon Record Office, Exeter
DCO	Duchy of Cornwall Office, Buckingham Gate, London
PRO	Public Record Office, London
RIC	Royal Institution of Cornwall, Truro
WDRO	West Devon Record Office, Plymouth

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